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**FLOW TESTS OF A SINGLE FUEL ELEMENT COOLANT CHANNEL
FOR A COMPACT FAST REACTOR FOR SPACE POWER**

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ABSTRACT

Water flow tests were conducted on a single fuel element cooling channel for a nuclear reactor concept being studied at the Lewis Research Center for space power. These tests established a method for measuring coolant flow rate, applicable to water flow testing of a complete mock-up of the reference reactor. The inlet plenum-to-outlet plenum pressure drop, which approximates the overall core pressure drop was also measured and correlated with flow rate. This information can be used for reactor coolant flow and heat transfer calculations. An analytical study of the flow characteristics was also conducted.

FLOW TESTS OF A SINGLE FUEL ELEMENT COOLANT CHANNEL
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SUMMARY

E-6651 A reference reactor has evolved as part of a technology program to study fast-spectrum, liquid-metal-cooled nuclear reactors for space power. The reactor is lithium-cooled, and has 247 uranium nitride-fueled cylindrical fuel elements. The fuel element coolant flow channels are annuli formed by the fuel elements and flow tubes which make up the core support structure. As a first step in studying the flow characteristics of the reference reactor concept, water flow tests were conducted on a single fuel element flow channel of the core. The testing was conducted with models of various annular gap sizes, since fabrication tolerances and clad expansion due to fuel swelling can cause deviations from the nominal gap width. The flow rates covered a Reynolds number range from about 10% to 150% of the design value.

The inlet plenum-to-outlet plenum pressure drop was measured and correlated with flow rate. This pressure drop, for the single channel model, approximates the pressure drop across the core of the complete reactor, and these correlations can be used for reactor heat transfer and coolant flow studies. For the nominal annular gap, and at the design operating conditions, the pressure drop with lithium is about 1.0 newtons/cm² (1.5 psi).

The tests also established a method for measuring the flow rate in the fuel element coolant channels, which can be used for the proposed testing with a complete reactor model. The method uses dummy fuel elements instrumented with two static pressure taps to measure the pressure drop along the channel. This instrumentation system was chosen over another system consisting of a pitot tube and static pressure tap.

An analytical study of the flow relationships was also conducted for comparison of analytical to experimental results. The calculated pressure drop for most of the conditions is lower than the experimental.

INTRODUCTION

A program is in progress at the Lewis Research Center to develop technology for a compact fast-spectrum, liquid-metal-cooled nuclear reactor, for space power. A reference reactor has evolved using concepts that look promising.

In order to conduct a detailed heat transfer analysis of the reference reactor, and to determine the coolant pumping requirements, it is necessary to establish the coolant flow characteristics of the reactor. This must be done experimentally, since an analytical treatment is inadequate, due to the somewhat complicated geometries in the reactor. As a first step in experimental flow studies, tests were conducted on a single fuel element flow channel, representative of the 247 channels existing in the core. The purposes of the tests were as follows:

1. To establish the correlation between flow rate, plenum-to-plenum pressure drop, and width of the annular coolant channel. This correlation is useful in determining the coolant pumping requirements, since the plenum-to-plenum pressure drop for the single channel model approximates the pressure drop of the complete reactor. The flow correlation for the single channel model is also useful in determining the effect of annulus width on flow rate in the complete reactor.
2. Another purpose of the tests was to establish a technique for measuring the flow rate in the fuel element coolant channels, which can be applied to flow testing of a complete reactor model. This involved determining suitable pressure measurement instrumentation and calibrating it against flow-rate. The proposed testing of a complete flow model would be for the purpose

of determining the flow distribution throughout the reactor.

Water at three temperatures was used to simulate the lithium coolant. Flow rates were varied to cover a range from about 10% to 150% of the design Reynolds number, which is about 4500 (ref. 1) in the fuel element annulus.

This report describes the experimental work on the single channel model. A description of the reactor, test considerations, and the experimental test facility is given. The test procedure, data reduction and sample data plots are then described. The results of the experimental work are presented, i.e., the selection of flow instrumentation for application to a complete flow model, the calibration curves to be used with this instrumentation, and the correlation between flow rate and plenum-to-plenum pressure drop. Finally, an analytical study is presented, with a comparison to experimental results.

REACTOR DESCRIPTION

The reference reactor is described in detail by Krasner, Davison, and Diaguila, (Ref. 1), and a brief description is given here. An overall view of the reactor is shown in figure 1. It is a lithium-cooled reactor with 247 uranium nitride cylindrical fuel elements supported in a honeycomb structure of bonded thin-wall tubing. There are side and end reflectors made of TZM (Mo-0.5Ti-0.1Zr). Six fueled rotatable control drums provide reactor control. The reactor components are enclosed in a pressure vessel which is about 57.7 cm (22.7 in) in diameter and 68.5 cm (27 in) long overall. T-111 (Ta-8W-2.4Hf) is the material for the pressure vessel, honeycomb support structure, and fuel element clad.

An annular coolant channel is formed between a fuel element and a tube of the honeycomb structure, having a nominal width of 1.016 mm (0.040 in). The fuel elements and honeycomb tubes have geometry features which affect the flow in the coolant channels and are important to the flow studies described in this report. They will therefore be described in more detail.

The fuel elements are 1.9 cm (0.75 in) in diameter and 43.8 cm (17-1/4 in) long overall. A photograph of a fuel pin mock-up is shown in figure 2, and figure 3 shows some typical fuel elements assembled in tubes of the core support structure. An anchor pin in the bottom of the fuel element restrains it axially. The anchor pin rotates into a groove in the end plate, forming a bayonet joint. A lock pin at the top of the fuel element prevents rotation of the anchor pin out of the groove. The honeycomb support structure for the core is made up of a welded cluster of thin-wall tubing attached to an end plate, as shown in figure 3. (Feasibility studies for fabrication of the structure are given in ref. 2). Inside of each tube are five reinforcing rings approximately equally spaced along its length. These rings have three internal projections equally spaced around the circumference. The projections on the three central rings have initial clearance with the fuel element to allow for expected diametral growth due to fuel swelling. They will restrain the fuel elements from excessive bowing due to non-uniform temperature distribution. The projections on the two end rings provide radial location. They are in contact with the fuel element end caps, which are outside of the fueled region, where no swelling is expected.

The reactor is cooled in a single pass with a flow of 9.4 kg/sec (20.7 lb/sec) of liquid lithium, at an inlet temperature of 1165°K (2100°R) and an outlet temperature of 1222°K (2200°R). The coolant is supplied from the inlet plenum (see fig. 1) and flows through the bottom end reflector, fuel element channels, top end reflector, to the outlet plenum. There is parallel flow through the fuel elements in the control drums, and around the control drums and side reflectors. A small amount of coolant also flows through the "triflute" regions, which are the interstices between clusters of three tubes in the stationary fuel section (see fig. 3), to prevent lithium from stagnating there.

TEST CONSIDERATIONS

Water was used for the flow testing to simulate the lithium coolant in the reactor for the following reasons: (1) water is readily available and easy to handle, (2) its kinematic viscosity at low temperatures is in the same range as the viscosity of the lithium coolant, and (3) because of its transparency, water lends itself to visual flow studies which would be included in the testing of a complete reactor flow model.

For closed conduit flow, characterized by the absence of a free liquid surface, which is the case for the reference reactor, viscous forces predominate. Under these conditions good hydraulic similitude between a flow model and a real device is attained if the model is to scale, and the Reynolds numbers are the same (ref. 3). When hydraulic similitude exists between the model and the real device, the "pressure coefficients" (ratio of static to dynamic pressure) at corresponding points are the same (ref. 4). The similitude conditions are met for the single channel tests (and the proposed complete model tests). In addition to this, the scale model is full size, and the kinematic viscosities of the water at the three test temperatures selected are in the viscosity range of the lithium coolant. Since

these additional conditions exist, not only are the pressure coefficients the same at corresponding points in the model and reactor, but the actual pressures (in terms of head of fluid) are identical, at the same Reynolds number and kinematic viscosity. The test results with water at the three selected temperatures are therefore strictly valid for lithium with the same kinematic viscosity. Possible errors in applying the test results for one viscosity (the viscosity at the test temperature) to another viscosity, due to imperfect similitude, are obviated.

The water temperatures selected for the flow tests are given in Table I. Also shown are the kinematic viscosities and the corresponding lithium temperatures.

TABLE I - Corresponding Water and Lithium Temperatures,
for the Same Kinematic Viscosity

Water test temperature	Kinematic viscosity	Lithium temperature
°K (°F)	m ² /sec (ft ² /sec)	°K (°R)
294 (70)	9.70×10 ⁻⁷ (10.45×10 ⁻⁶)	617 (1110)
311 (100)	6.88×10 ⁻⁷ (7.41×10 ⁻⁶)	914 (1645)
329 (133)	5.05×10 ⁻⁷ (5.43×10 ⁻⁶)	1194 (2150)

Water at 329°K (133°F) was selected since it has the same kinematic viscosity as lithium at 1194°K (2150°R)-the average coolant temperature in the core at design operating conditions. Lower temperature water was included in the program, for studying flow characteristics at off-design conditions.

Flow rates were chosen to cover a range of about 10% to 150% of the design Reynolds number, resulting in flow in both the laminar and turbulent regions.

APPARATUS

Single Channel Flow Mock-up and Test Facility

The test model is a full-scale duplication of the flow channel for a single fuel element in the central portion of the core of the reference reactor design, in which the end reflector thickness is 5.08 cm (2.0 in). It mocks up the fuel element flow conditions existing in the reactor, with the exception of the trifiute flow. The model consists of a dummy fuel element, flow tube, 5.08-cm-(2.0 in) thick end plates with 0.635-cm-(0.25 in) diameter flow passages to simulate end reflectors, and plenum chanbers at the inlet and outlet ends of the model. Photographs of the dummy fuel element and assembled test model are shown in figures 2 and 4, respectively, and a schematic of the model is shown in figure 5.

The nominal design dimension of the annular gap between the fuel element outside diameter and flow tube inside diameter for the reference reactor is 1.016 mm (0.040 in). Due to fabrication tolerances the actual annular gaps could vary from the nominal. In addition, fuel swelling in the reactor (as discussed in ref. 1) causes radial expansion of the fuel element, which reduces the annular gap. For determining the effect of annular gap size on the flow characteristics, models were constructed with various annular gap sizes. Two dummy fuel elements and three flow tubes were used to obtain five annular gap sizes from 0.840 mm (0.0331 in) to 1.160 mm (0.0457 in). Two of the flow tube models were made of brass, and the one shown in figure 4 was made of plexiglas. Visible through the tube are the three central reinforcing rings (which have the three internal preprojections for restraining the fuel element).

Fabrication tolerances can also result in the fuel element being not perfectly concentric with the tube, which would change the local gap width at the static taps and pitot tube, and might affect the pressure measurements. To study the effect of eccentricity, one of the flow tubes was modified to accept three fuel element positioning screws at two axial locations, replacing the projections at these locations. The ends of the screws had the same radius as the projections.

Figure 6 shows a schematic of the test facility, which provides a hot and cold tap water supply, with throttle valves for obtaining the required temperatures and flow rates.

Instrumentation

Two systems for measuring the fuel element coolant flow, which could be used for the proposed complete reactor flow model testing, were investigated. The methods used a pressure characteristic in the fuel element coolant channel with a calibration against flow rate. One system, called the "fuel element pressure drop" method, measured the static pressure drop along a section of the flow channel. The instrumentation for this system consisted of two static pressure taps, 36.6 cm (14.4 in) apart, drilled into the wall of the fuel element. The other system, which was investigated during the early phase of the test program, was the "dynamic head" method. The instrumentation for this system was the downstream static tap and a pitot tube at the same axial location. The diameter of the static taps and the inside diameter of the pitot tube were 0.0381 cm (0.015 in). The location of the pressure taps is shown in figure 5.

The differential monometers, thermometers, and flow rate measurement system are shown schematically in figure 6. The flow rate was measured by two calibrated turbine flowmeters. A $63 \text{ cm}^3/\text{sec}$ (1 gpm) meter was used for the low flow range, and a $315 \text{ cm}^3/\text{sec}$ (5 gpm) meter covered the high range. The flowmeter output is an electrical pulse, the rate being measured and displayed by a digital "eput" (events per unit time) meter.

TEST PROCEDURE

Before assembling a flow model for testing, measurements were made of the fuel element outside diameter and flow tube inside diameter, to determine the annular gap. A number of measurements were made along their lengths, for an average reading. The pitot tube was positioned to be at the midpoint between the fuel element and flow tube, and the pitot tube axis was aligned parallel to the fuel element axis. The fuel element was then inserted into the flow

tube. For the test models using the flow tubes that had the five standard reinforcing rings (see fig. 3), measurements were made of the eccentricity between the fuel element and flow tube. For the series of tests to study the effects of eccentricity, a model was modified to incorporate adjusting screws, replacing some of the ring projections. By adjusting the screws in or out of the tube, one could obtain any desired off-center eccentricity of the fuel element.

After assembly of the model was completed, the test run was started. The hot and cold water supplies were regulated by throttle valves (see fig. 6) to obtain the desired water temperatures of 294°K (70°F), 311°K (100°F), and 329°K (133°F), and flow rates from about 13 cm³/sec (0.2 gpm) to 250 cm³/sec (4.0 gpm). Readings were taken of (1) fuel element pressure drop, (2) dynamic head, (3) plenum-to-plenum pressure drop, (4) flow meter pulse rate, and (5) water temperature.

DATA PRESENTATION AND SAMPLE DATA PLOTS

The data of fuel element pressure drop and plenum-to-plenum pressure drop was plotted against flow rate, for each test set-up of annular gap size, and for the three test temperatures. Two plots were made for each set of data, as shown in figures 7 and 8, - one for the complete flow range, and another, on an expanded scale, for the low flow range.

Cross plots of the data were then made (logarithmically, to facilitate curve fitting), of pressure drop versus annular gap, with flow rate as the parameter, as shown in figures 24 to 35 of Appendix A.

The cross plots were desirable since there was some error associated with obtaining an average measurement of the annulus width, and there were variations in the geometry of the reinforcing rings. The best smooth curves were fitted to the plotted points, to minimize these effects, for the final correlations.

Final correlation curves were constructed, based on the cross plots. These are correlations of fuel element pressure drop and plenum-to-plenum pressure drop versus flow rate, for even gap sizes (in inches), from 0.813 mm (0.032 in) to 1.168 mm (0.046 in). They are shown as figures 9 to 20, under "Results and Discussion."

RESULTS AND DISCUSSION

Selection of Instrumentation System

Initially, two methods to measure the fuel element coolant flow were investigated, for application to the complete reactor mock-up flow tests - the "fuel element pressure drop" method, and the "dynamic head" method, described in the Instrumentation Section. The fuel element pressure drop method was eventually chosen, for the following reasons:

(1) The sensitivity is about twice that of the dynamic head

(2) The dynamic head measurement is very dependent upon the radial position of the fuel element with respect to the tube. This radial position affects the width of the annulus at the pitot tube, due to eccentricity between the fuel element and flow tube. This was shown by tests where the fuel element was rotated to various positions with respect to the tube. In one of these tests, the dynamic head varied 24% from the mean value.

On the other hand, the fuel element pressure drop measurement is relatively insensitive to radial positioning and local variations in annular gap at the static tap. The variations in fuel element pressure drop was less than 1-1/2%. In another series of tests, where a 0.10 mm (0.004 in) eccentricity between the fuel element and tube was purposely introduced into the model, there was no significant change in the fuel element pressure drop. (This 0.10 mm eccentricity is greater than that measured in the several test models, and also more than the tolerance for the reference design and the complete reactor flow mock-up).

(3) It is more difficult to fabricate the pitot tube than the static taps. Also, the position and attitude tolerances of the pitot tube may be quite critical.

(4) The pitot tube can be damaged or misaligned during handling and installation of the fuel element.

Flow Rate Calibration Curves

From the test results, a series of curves have been generated and are presented in figure 9 through 14, in which the static pressure drop along the fuel element is plotted against flow rate with gap size as a parameter. These are the calibration curves for the "fuel element pressure drop" instrumentation system. Two sets of curves for each temperature are given - one for the complete flow range, and another, using an expanded scale for better resolution, for a low flow range. The lower flow rate range is below the design operating conditions. The curves are for even-dimensioned gaps (in inches), from 0.813 mm (0.032 in) to 1.168 mm (0.046 in).

Inlet Plenum-to-Outlet Plenum Pressure Drop

The correlation of the inlet-to-outlet plenum pressure drop with respect to flow rate for various annular gap sizes and temperatures are presented in figures 15 to 20. This pressure drop for the single channel tests is approximately the pressure drop across the core of the complete reactor. There is a small difference due to the triflute flow not being mocked up in the single channel tests. A correction for this can be calculated, however, as shown in Appendix B. Briefly, it involves calculating the increase in ΔP across the top and bottom reflectors due to the triflute flow, which is supplied from the same holes in the reflectors that supply the fuel element flow. It should be noted that the correction in plenum-to-plenum ΔP due to the triflute flow is only about 5-1/2%, and may be considered unnecessary.

In addition to having triflute flow, the complete reactor will also have pressure gradients in the plenums, which affect the flow to fuel elements at different locations. The pressure drop that is mocked up by the single channel model is therefore actually the "local" plenum-to-plenum pressure drop in the complete reactor, i.e., the ΔP between a point at the entrance to a bottom

reflector coolant hole for a fuel element, and a point at the exit from the corresponding hole in the top reflector. Even with this limitation, however, the single channel flow correlations are useful in the following ways:

- (1) An approximate pressure drop across the core can be determined, for a given flow rate, neglecting pressure gradients in the plenums. For design conditions this pressure drop is 1.0 newtons/cm^2 (1.5 psi) for lithium, which includes the triflute flow correction.
- (2) Analyses can be made of the effects on flow conditions (and therefore heat transfer) of annular gap variations due to fabrication tolerances and fuel swelling. E.g., a 1% diametral growth of the fuel pin would cause about 10-12% reduction in flow rate, for the same core ΔP .
- (3) Flow conditions can be determined for off-design coolant temperatures.
- (4) The correlations would be used if local plenum-to-plenum static taps are installed as part of the fuel element flow rate measuring system, as described in the "Applications" section.

Uncertainty of Correlations

There is a 95% probability (corresponding to two standard deviations) that the fuel element calibration curves show the true flow rate to within about $\pm 4\%$, except for the low flow rate range, below $20 \text{ cm}^3/\text{sec}$ (0.32 gpm), where the uncertainty is about 10%. For the plenum-to-plenum correlation curves, the two standard deviation value is 3%, except for the low range, where it is 7%. It is felt that the two standard deviation values give reasonable confidence that when using the correlation curves, the true flow rate is within the stated limits.

The uncertainty is due to (1) a flow meter inaccuracy of 1/2% of the reading, (2) an allowable manometer zero offset of 0.1 inch of water, (3) random errors in the manometer readings (the two standard deviation values were calculated from the basic data of pressure drop versus flow rate), and (4) random errors in the geometry of the models (the two standard deviation values were calculated from the cross plots of pressure drop versus annular gap).

Analytical Correlations

Correlations of fuel element pressure drop and inlet plenum-to-outlet plenum pressure drop versus flow rate and annular width were determined analytically, for comparison with the experimental results. These pressure drops were obtained as the sum of individual irreversible pressure losses for various flow restrictions (or impedances) in the flow passage. The calculations were made for the same annulus widths, water temperatures, and flow range as for the experimental tests. The calculations were based on the following general formulas, as found in ref. 4:

Skin friction pressure losses in annuli and circular holes

$$\Delta p = \frac{\rho V^2 f L}{2 g D_h}$$

Expansion pressure losses

$$\Delta p = \frac{\rho (V_1 - V_2)^2}{2 g}$$

Contraction pressure losses

$$\Delta p = \frac{K \rho V_3^2}{2 g}$$

where

Δp irreversible pressure loss

V average velocity in annulus or circular hole

V_1 average velocity before expansion

V_2 average velocity after expansion

V_3 average velocity after contraction

f friction factor ($f = \frac{16}{R}$ for laminar region, $f = \frac{0.076}{R^{0.25}}$ for turbulent region)

R Reynolds number

L length of annulus or circular hole

D_h hydraulic diameter

- K contraction coefficient for a particular restriction
 g gravitational constant
 ρ fluid density

For the "fuel element pressure drop" (the difference in static pressure between the fuel element static taps, spaced 36.6 cm (14.4 in) apart), calculations were made of the pressure losses for the following individual impedances, which can be visualized from the flow model schematic, figure 5:

1. Skin friction in annular passage between fuel element and flow tube
2. Skin friction in annular passage between fuel element and reinforcing ring.
3. Sudden contraction to reinforcing ring, from annulus.
4. Sudden expansion from ring to annulus.
5. Contraction around projections in ring.
6. Expansion around projections in ring.

For the "inlet plenum-to-outlet plenum pressure drop", calculations were made for the following additional impedances:

7. Sudden contraction from inlet plenum to circular hole in bottom reflector.
8. Skin friction in circular holes in top and bottom reflectors.
9. Diverging annulus, to fuel pin.
10. Contraction to anchor pin, at bottom
11. Expansion from anchor pin

12. Expansion from fuel element annulus
13. Contraction around locking head, on top of fuel pin
14. Expansion from locking head
15. Contraction to circular hole in top reflector
16. Sudden expansion from circular hole in top reflector to outlet plenum chamber.

A comparison of the analytical and experimental results for the fuel element pressure drop and the plenum-to-plenum pressure drop versus gap for different flow rates is presented in figures 21 and 22. The typical curves are for a water temperature of 329° K (133° F). The agreement between the experimental and analytical results is fairly good. For example, at design conditions, the fuel element pressure drop obtained analytically is 14% below the experimental, and the analytical plenum-to-plenum pressure drop is 11% below the experimental. The calculated pressure drop for most of the conditions is lower than the experimental.

The analytical study was useful in estimating the triflute flow correction for the plenum-to-plenum pressure drop (described in Appendix B). It was also useful in correcting one of the experimental runs where some of the reinforcing rings were separated slightly from the flow tube. This separation increased the effective ring thickness, and therefore the pressure drop across the rings. An estimate of the magnitude was calculated, and subtracted from the experimental results, to obtain a "normalized" run.

Application of Single Flow Channel Results to Measurement of Fuel Element Flow Rate in the Complete Reactor Model Tests

Tests with a flow model of the complete reactor have been proposed for determining the flow distribution in the reactor and adjusting it by orificing, if necessary. For these tests flow rate instrumentation would be installed in various fuel element flow passages. With additional instrumentation for measuring the flow through the several other regions, such as around the control drums, the complete flow distribution of the reactor would be determined.

There is one complication in applying the calibrated flow instrumentation to the fuel element flow rate measurements. The flow rate is dependent upon the width of the annulus which can vary from one fuel element flow channel to another, due to fabrication tolerances. Considering this, the following approaches could be taken, using either the fuel element

ΔP static taps alone, or a combination of the fuel element ΔP static taps and static taps to measure the local plenum-to-plenum pressure drops.

For measurements with the fuel element ΔP static taps,

1. Each annular gap could be measured, and the appropriate calibration curve used.

2. A spot flow calibration could be made on each fuel element flow passage, to determine the effective annular gap.

3. It could be assumed that all flow channels had the nominal design annular gap of 1.016 mm (0.040 in), and just use the calibration curve for this gap. If this approach were used, there would be a possible error in the measurements - the amount depending upon the flow conditions. At design conditions of 72.5 cm³/sec (1.15 gpm) flow rate per fuel element and a water temperature of 329°K (133°F), the flow rate error would be -18% if the gap were actually the maximum allowable (1.138 mm, or 0.0448 in),

and + 10% if the gap were the minimum allowable (0.957 mm, or 0.0377 in).

If measurements were made with the fuel element static taps and plenum-to-plenum static taps, the annular gap and flow rate common to both pressure drop measurements could be established. An example of the procedure is given for a hypothetical case, with the following conditions: water temperature, 329°K (133°F); fuel element ΔP , 1.0 meters (3.3 ft) of water; plenum-to-plenum ΔP , 2.2 meters (7.2 ft) of water. From the fuel element correlation curve, figure 13, and the plenum-to-plenum curve, figure 19, determine the flow rates for the various annular gaps and the measured pressure drops. Plot the data of flow rate versus annular gap for the two measured pressure drops, as illustrated in figure 23. The intersection of the two curves shows that the annular gap for that particular fuel element coolant channel would have to be 0.965 mm (0.038 in). The flow rate for the conditions given would be 70 cm³/sec (1.1 gal/min.).

The best location for the static taps for the local plenum-to-plenum pressure drop measurements would probably be in the 0.635 cm - (0.25 in) diameter reflector flow passages (see fig. 5). At this location the pressure taps would measure a pressure drop that was slightly lower than in the single channel model, due to the plenum-to-flow passage pressure losses. A correction for these pressure losses could be calculated, however.

SUMMARY OF RESULTS

Water flow tests were conducted on a mock-up of a single fuel element flow channel of the reference design lithium-cooled fast reactor. The tests were conducted with water at 329°K (133°F), 311°K (100°F), and 294°K (70°F), and covered a flow rate range from about 10% to 150% of the design Reynolds number. The results are as follows:

1. A static tap instrumentation technique was established to measure the flow rate in the fuel element coolant channels of a complete reactor flow model. This technique uses static pressure taps to measure the irreversible pressure loss along a section of a fuel element, with a calibration of flow rate versus pressure drop. The calibration curves are plotted for a range of annulus widths. Initially another system was investigated, which measured a dynamic head. The "fuel element pressure drop" technique was chosen, however, as being the most suitable.
2. A correlation is presented for the inlet plenum-to-outlet plenum pressure drop versus flow rate, which approximates the characteristics of the complete core. It includes the effect of annular gap size.
3. From the above correlations it was determined that the pressure drop across the core of the reference design reactor operating at design conditions is about 1.0 newtons/cm² (1.5 psi).
4. A comparison of analytical and experimental results showed agreement within 14% for the fuel element pressure drop, and 11% for the plenum-to-plenum pressure drop, at design conditions. The analytical values were lower than the experimental.
5. Various procedures have been established for determining the flow rates in the fuel element coolant channels of the proposed complete reactor flow model.

APPENDIX A

CROSS-PLOT CORRELATIONS OF FUEL ELEMENT PRESSURE DROP
AND PLENUM-TO-PLENUM PRESSURE DROP VERSUS ANNULAR GAP

Presented herein are the cross-plot correlations of fuel element ΔP and plenum-to-plenum ΔP versus annular gap, for selected flow rates. The plotted points were taken from the original data curves of pressure drop versus flow rate, and were plotted logarithmically, to facilitate curve fitting. From these cross plots, final correlation curves were constructed of pressure drop versus flow rate (figs. 9-20).

Fig. No.Fuel Element Pressure Drop Curves

294°K (70°F) water temp, low flow rate range	24
294°K (70°F) " " high " " "	25
311°K (100°F) " " low " " "	26
311°K (100°F) " " high " " "	27
329°K (133°F) " " low " " "	28
329°K (133°F) " " high " " "	29

Plenum-to-Plenum Pressure Drop Curves

294°K (70°F) water temp, low flow rate range	30
294°K (70°F) " " high " " "	31
311°K (100°F) " " low " " "	32
311°K (100°F) " " high " " "	33
329°K (133°F) " " low " " "	34
329°K (133°F) " " high " " "	35

APPENDIX B

CALCULATION OF PLENUM-TO-PLENUM PRESSURE DROP IN COMPLETE REACTOR,
INCLUDING CORRECTION FOR TRIFLUTE FLOW

In the single channel flow test model the triflute flow was not simulated. The relationship between flow rate and local plenum-to-plenum pressure drop for the complete reactor core is therefore not exactly the same as for the single channel model. However, if desired, a small correction can be made to account for this. It is based on the experimental tests and the analytical studies. The detailed procedures for obtaining the corrected plenum-to-plenum pressure drop for the complete reactor is presented as an example, for design conditions. Briefly, the procedure is to add the increased pressure drop across the end reflectors due to the triflute flow, to the single channel results.

The conditions for the example are as follows:

- a. Total mass flow rate of lithium: 9.39 kg/sec (2.07 lbs/sec)
- b. Lithium temperature: 1194°K (2150°R),
water temperature: 329°K (133°F)
- c. Width of annulus: 1.016 mm (0.040 in).
- d. Flow distribution: 10% around control drums and side reflectors, 6% through triflute regions, 84% to fuel elements. This is the nominal design flow distribution (ref. 1).
- e. Volume flow rate of lithium or water per fuel element, based on the total 247 fuel elements: 72.5 cm³/sec.
- f. Volume flow rate to triflute regions supplied by one of the holes in the reflector: 7.1 cm³/sec. This is based on 181 holes in the reflector which supply coolant to the 181 stationary fuel elements and also the triflute regions.

Figure 36 shows a schematic of the flow passages for a typical fuel element and triflute region.

The procedure for making the calculation can be expressed mathematically as follows:

$$\Delta P_T = \Delta P_1 + K(\Delta P_2 - \Delta P_4) - K(\Delta P_1 - \Delta P_3)$$

The definitions of the terms, the procedures for obtaining their values, and the design condition example are as follows:

ΔP_T total plenum-to-plenum ΔP which includes the trifiute flow correction. This is the ΔP across the core of the complete reactor.

ΔP_1 plenum-to-plenum ΔP for flow rate of 72.5 cm³/sec. From fig. 19 the value is 2.20 meters of water.

ΔP_2 plenum-to-plenum ΔP for flow rate of 79.6 cm³/sec, which includes 7.1 cm³/sec for the trifiute flow. From fig. 19 the value is 2.55 meters of water.

ΔP_3 fuel element ΔP for a flow rate without the trifiute flow (72.5 cm³/sec). From fig. 13 the value is 0.92 meters of water.

ΔP_4 fuel element ΔP for a flow rate which includes the trifiute flow (79.6 cm³/sec). From fig. 13 the value is 1.10 meters of water.

K The sum of the ΔP across each reflector divided by the sum of the ΔP from the inlet plenum static tap to the upstream fuel element static tap and the ΔP from the downstream fuel element static tap to the outlet plenum static tap. The value is 0.74, as determined by the analytical program, for design conditions. The value does not change significantly for other conditions of flow rate, water temperature, or annular gap.

$K(\Delta P_2 - \Delta P_4)$ The ΔP across the end reflectors for the flow rate which includes the triffute flow ($79.6 \text{ cm}^3/\text{sec}$). The value is calculated to be 1.07 meters of water.

$K(\Delta P_1 - \Delta P_3)$ the ΔP across the end reflectors for the flow rate without the triffute flow ($72.5 \text{ cm}^3/\text{sec}$). The value is calculated to be 0.95 meters of water.

The triffute flow correction is the difference in ΔP across the end reflectors for flow rates with the triffute flow and without the triffute flow, $K(\Delta P_2 - \Delta P_4) - K(\Delta P_1 - \Delta P_3)$, or 0.12 meters of water.

This is to be added to the single channel plenum-to-plenum pressure drop (ΔP_1), to obtain the pressure drop across the complete reactor core (ΔP_T).

For the example, at design conditions, the reactor core pressure drop is then 2.32 meters of water, or lithium with the same kinematic viscosity, and is equivalent to $1.01 \text{ newtons/cm}^2$ (1.46 psi) for lithium. It should be noted that this is actually the "local" plenum-to-plenum pressure drop, as discussed in the test, since the pressure in the plenums is not uniform.

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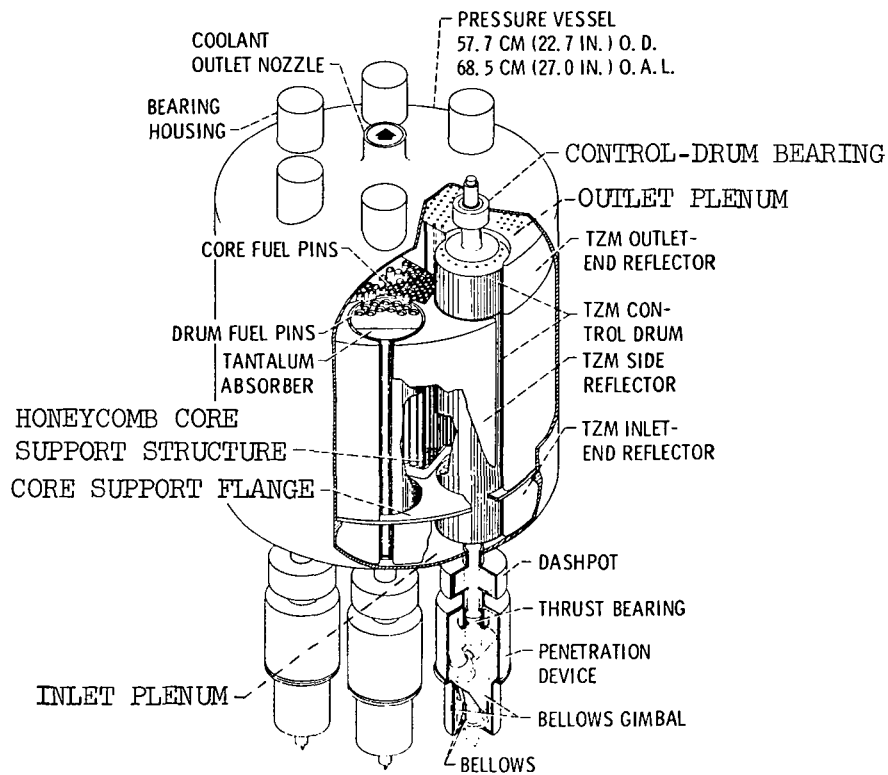
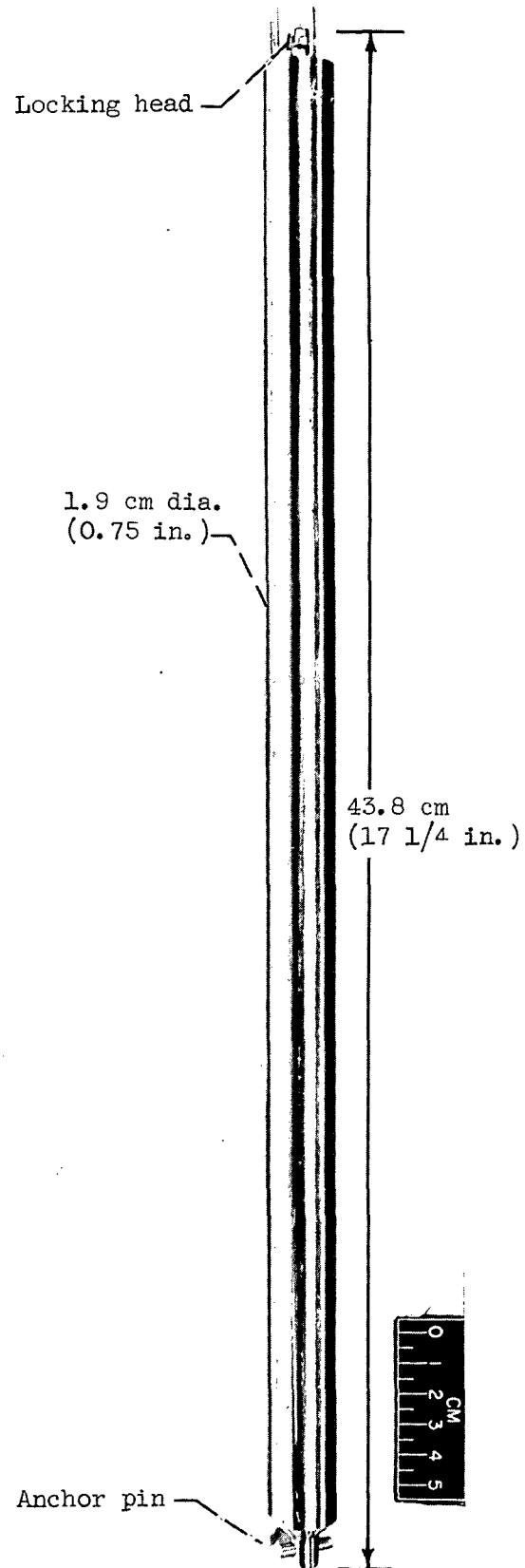


Figure 1. - Compact fast reactor-reference design.



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Figure 2. - Fuel element mockup for single channel tests.

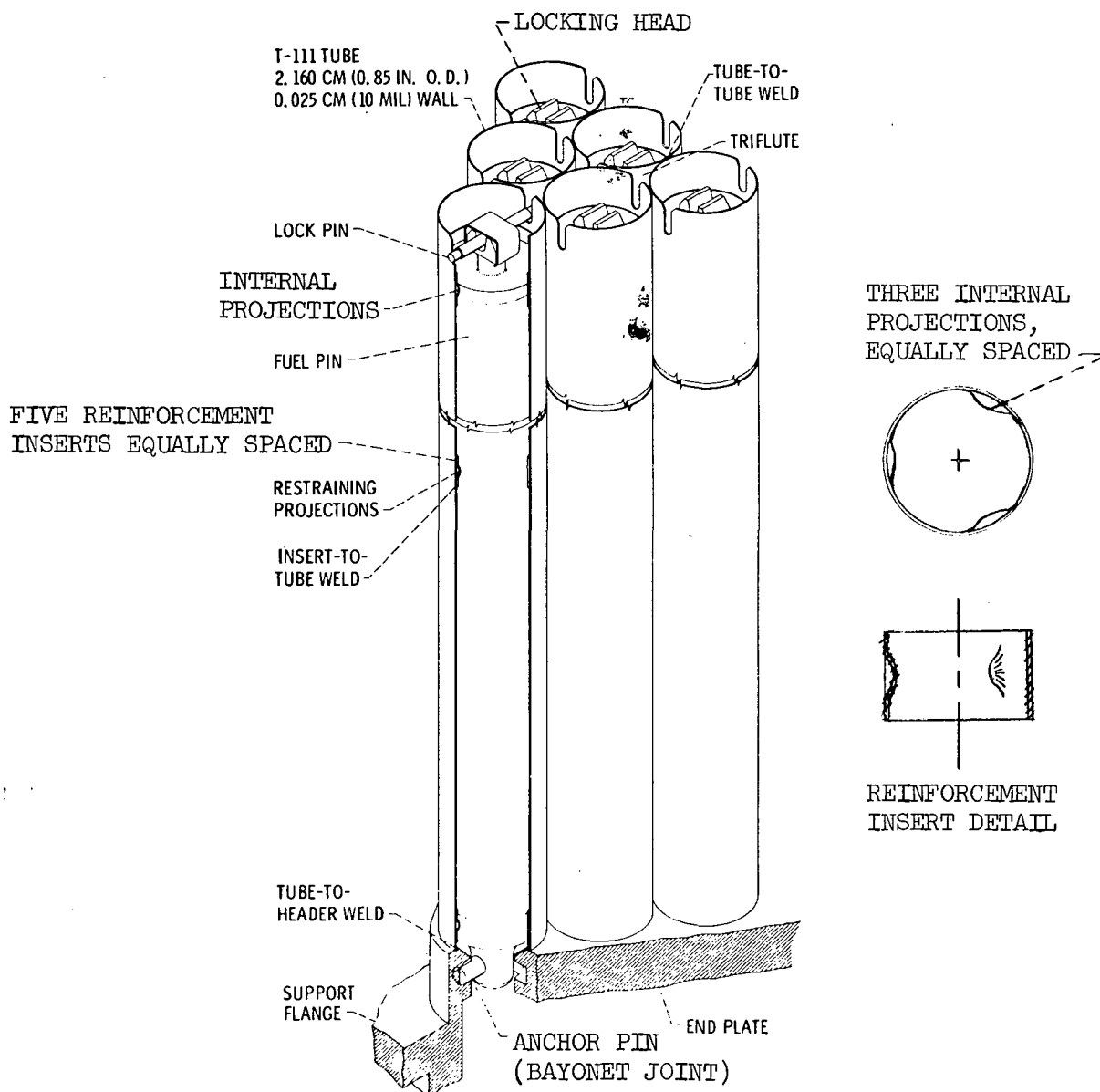


Figure 3. - Core support structure-Honeycomb concept.

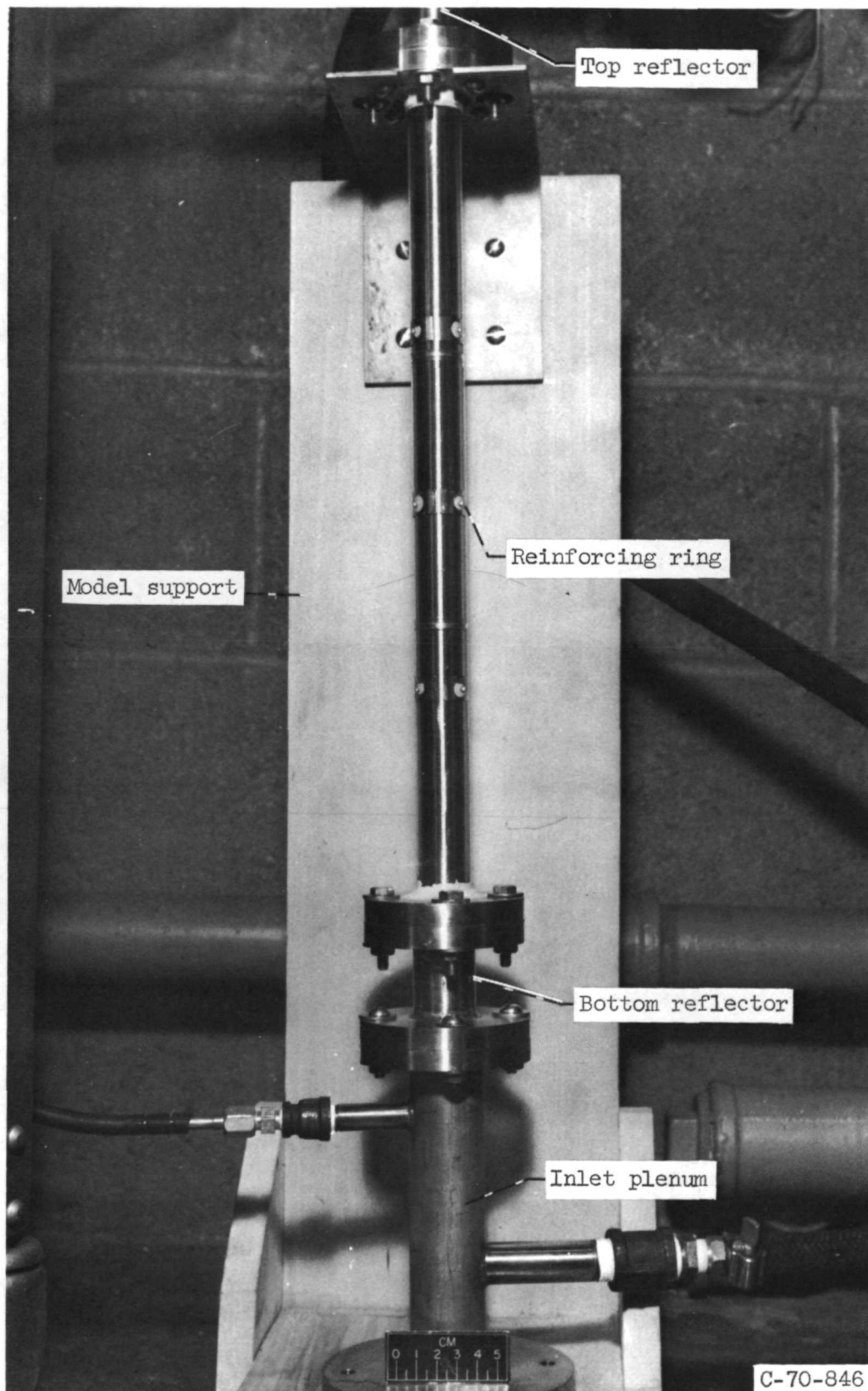


Figure 4. - Flow model.

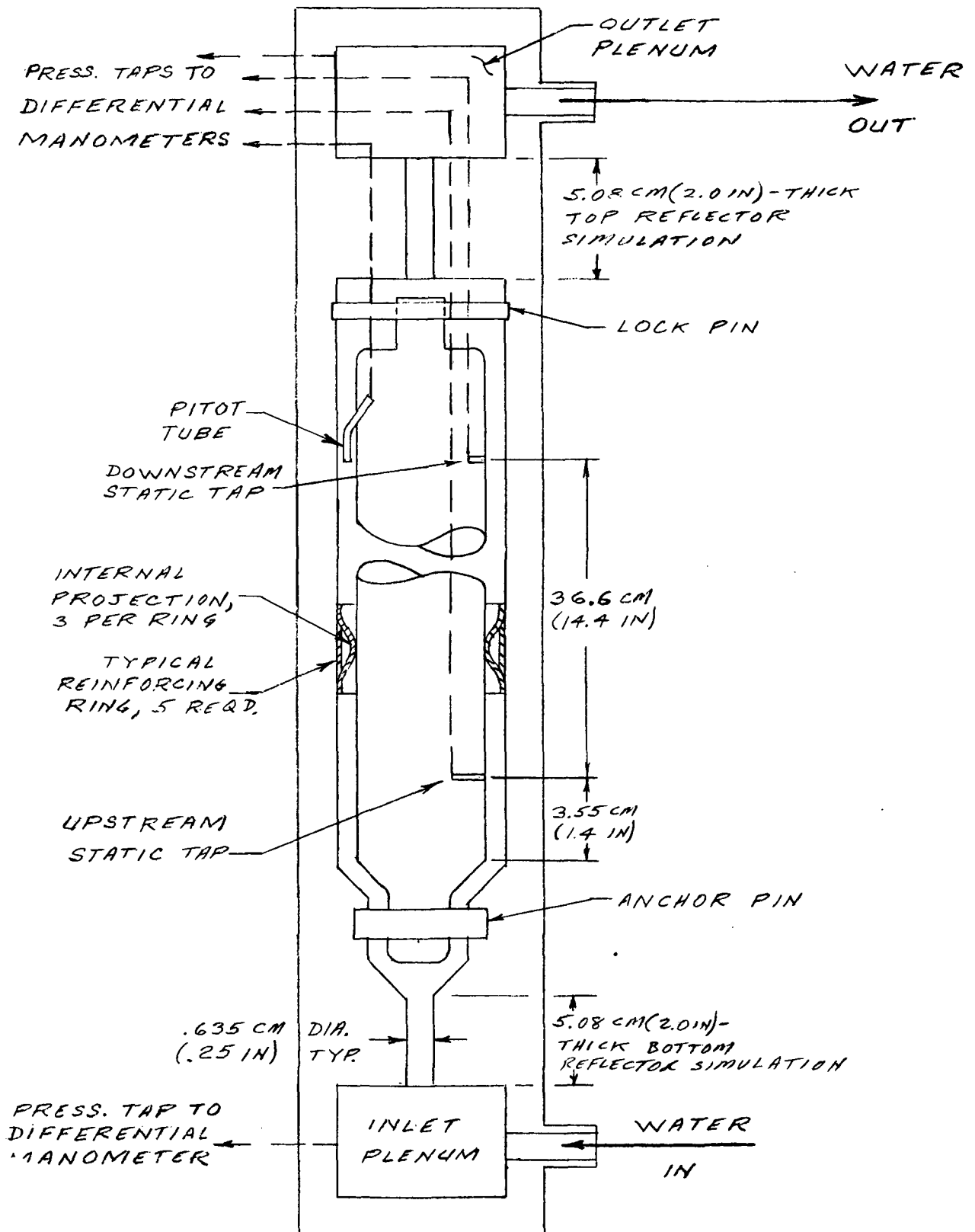


FIG. 5 SCHEMATIC DIAGRAM OF SINGLE CHANNEL FLOW MODEL

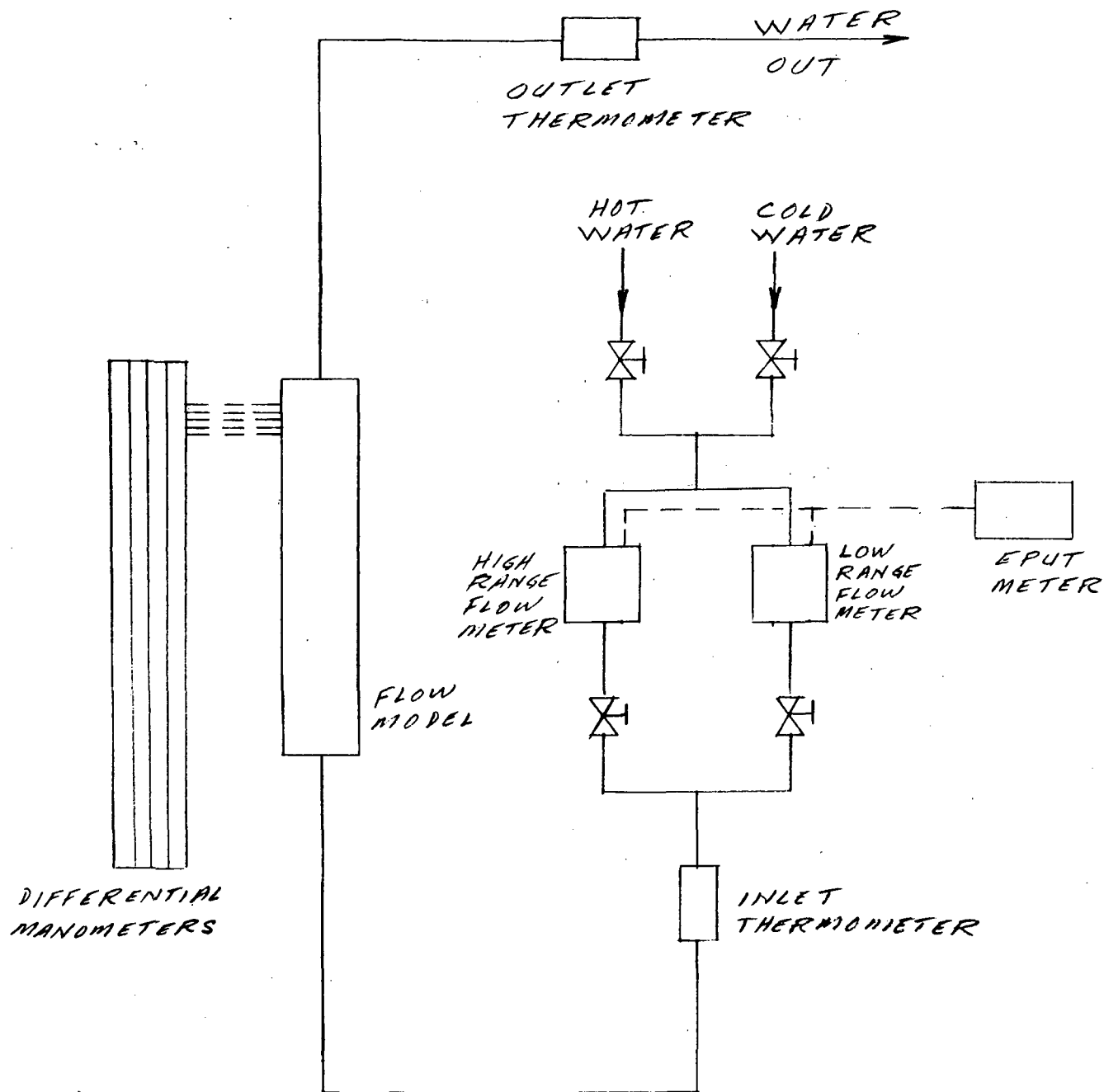
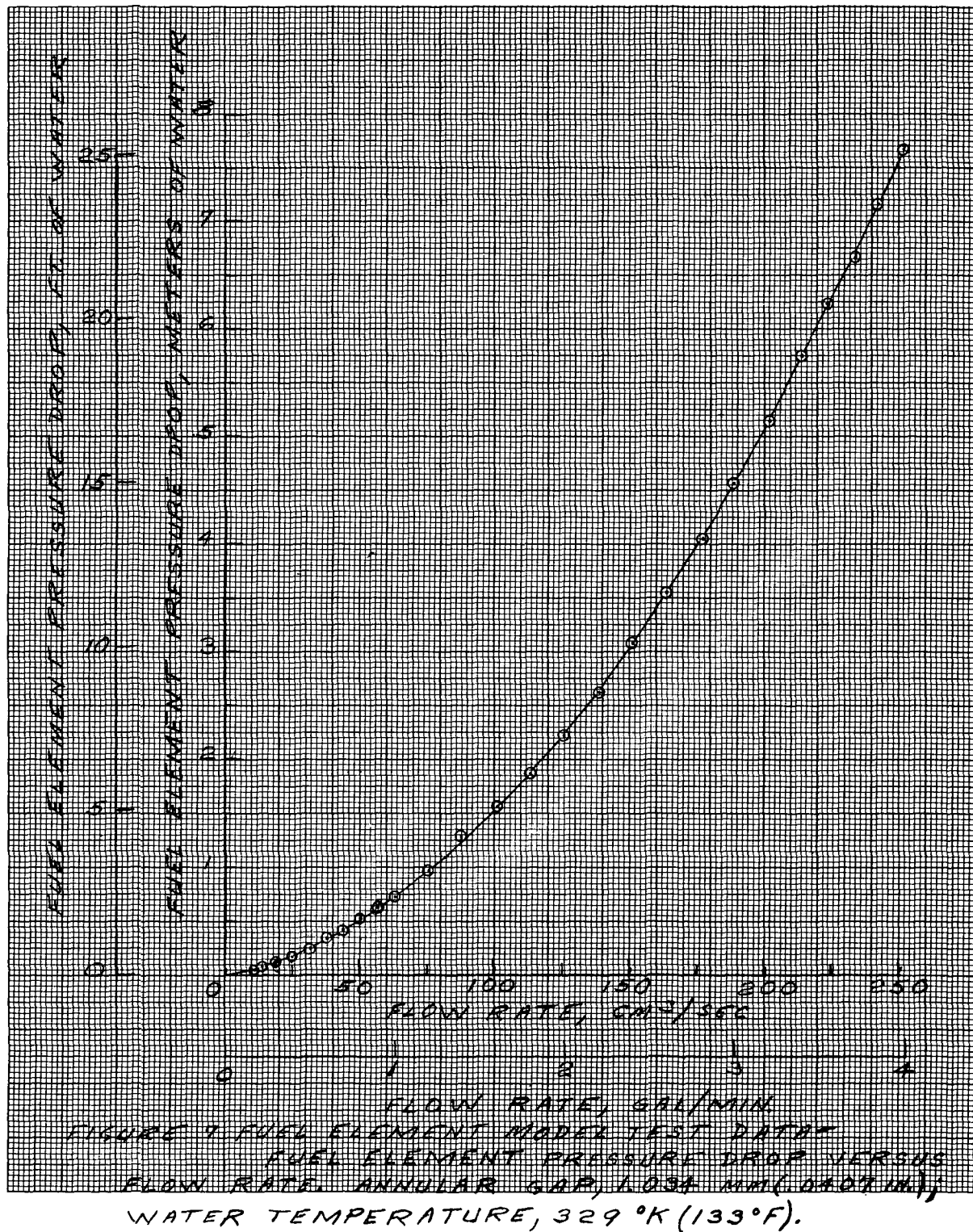


FIG. 6 SCHEMATIC DIAGRAM OF TEST FACILITY AND INSTRUMENTATION



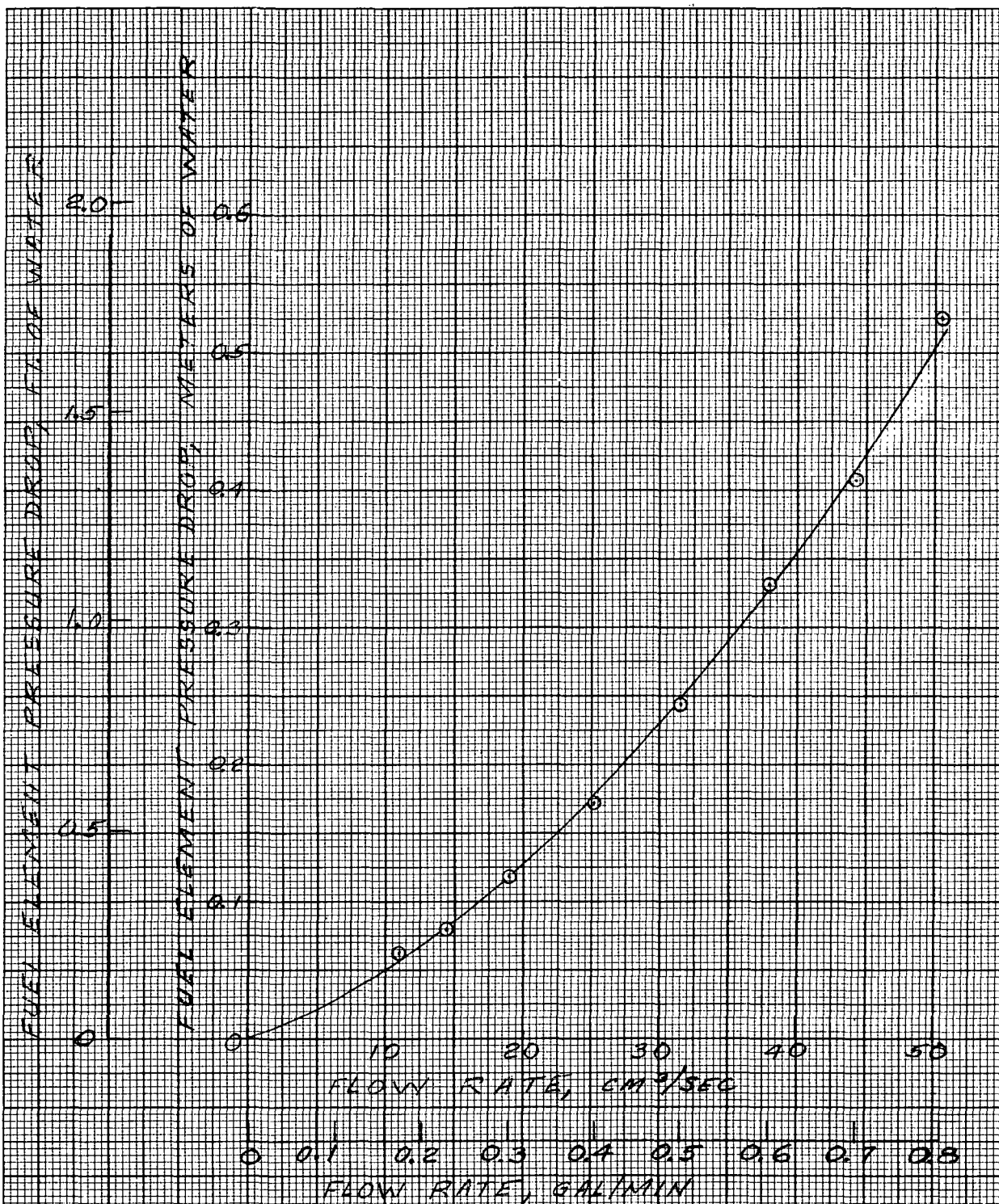


FIGURE 6 FUEL ELEMENT MODEL TEST DATA FOR LOW FLOW RATE RANGE - FUEL ELEMENT PRESSURE DROP VERSUS FLOW RATE.
ANNULAR GAP, 1.034 MM (0.0407 IN.);
WATER TEMPERATURE, 329 °K (133 °F)

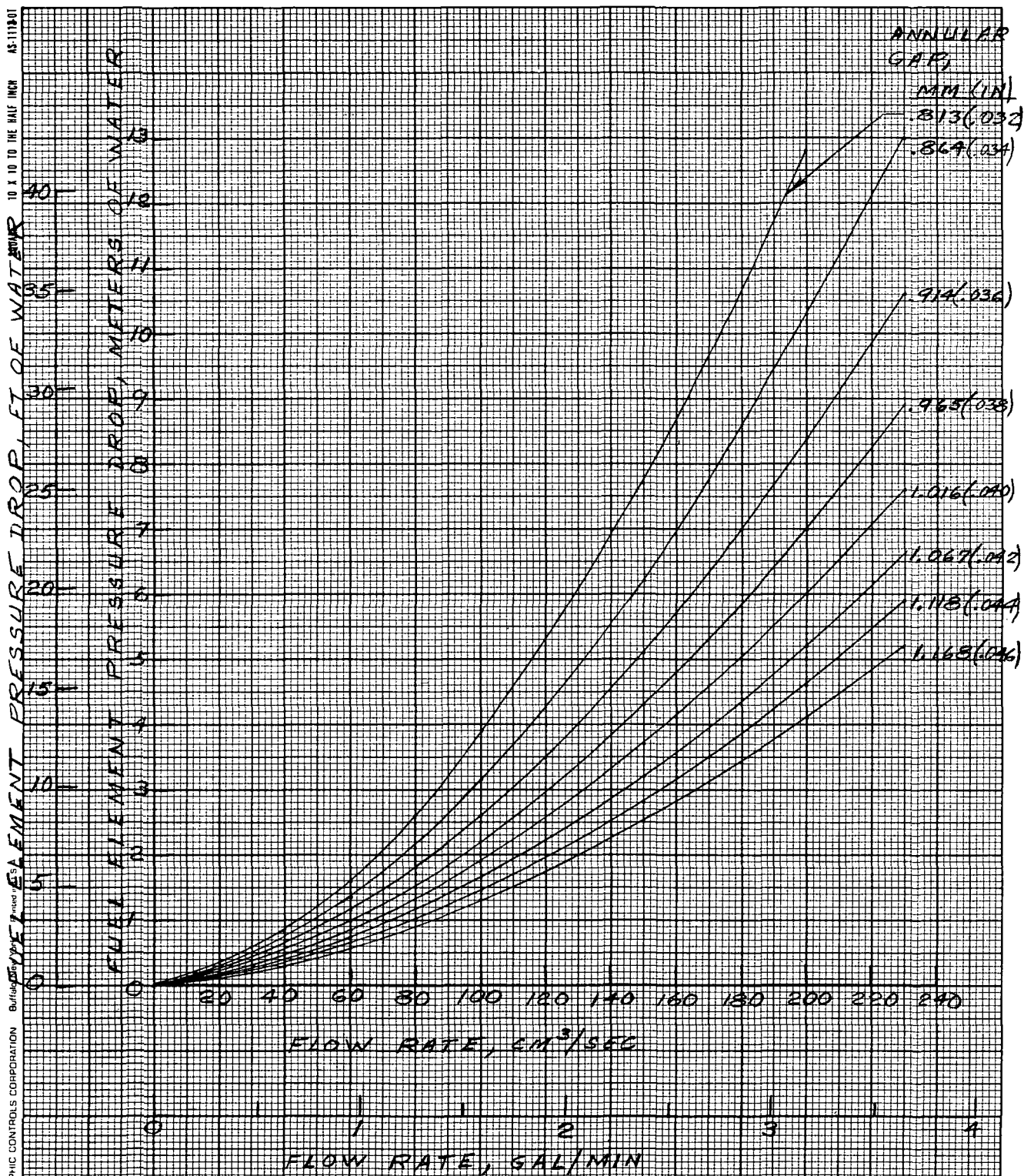


FIGURE 9 CALIBRATION CURVES OF FUEL ELEMENT PRESSURE DROP VERSUS FLOW RATE. WATER TEMPERATURE, 294°K (70°F)

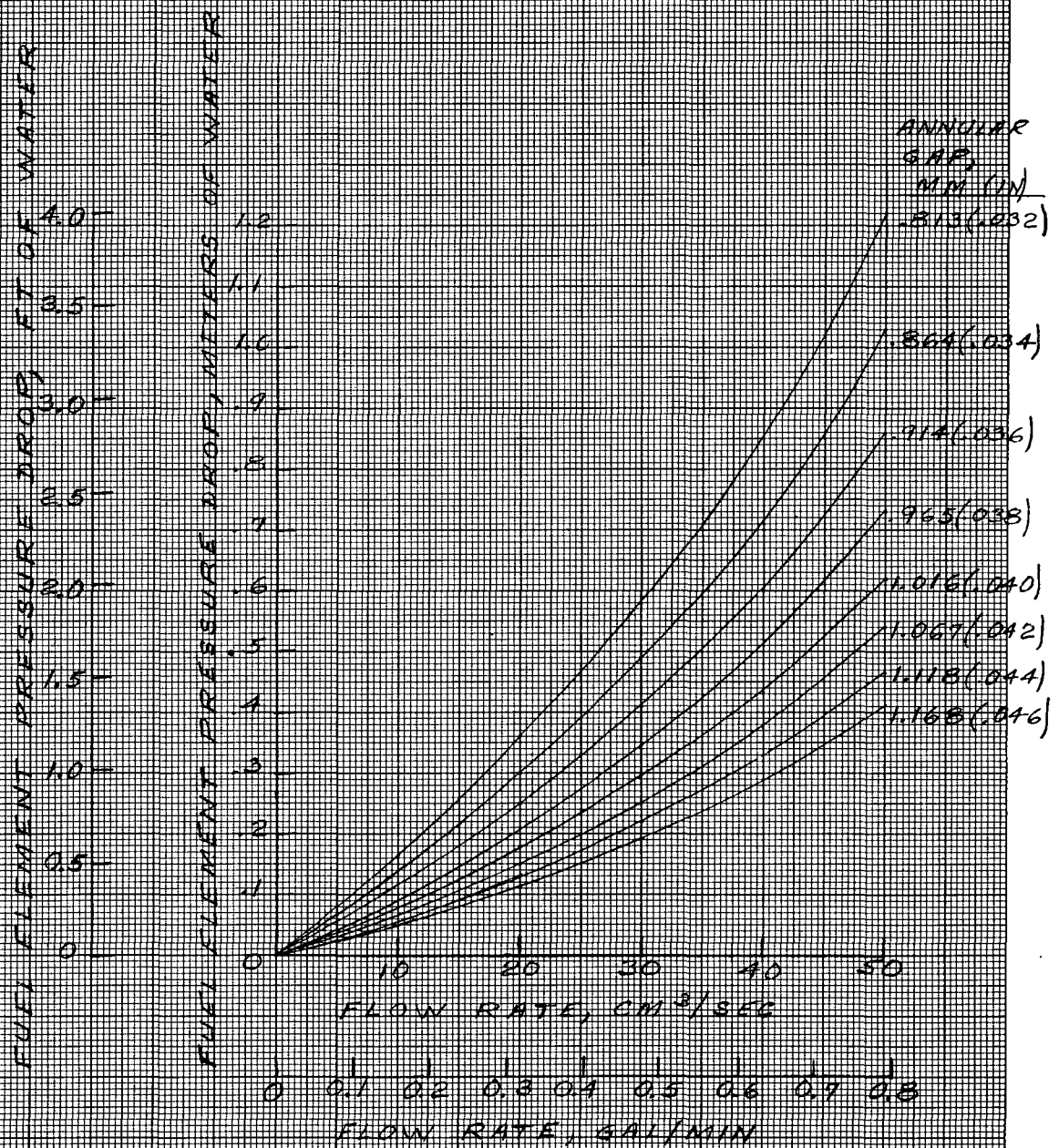


FIGURE 10 CALIBRATION CURVES OF FUEL ELEMENT PRESSURE DROP VERSUS FLOW RATE, LOW FLOW RATE RANGE, WATER TEMPERATURE, 294°K (70°F)

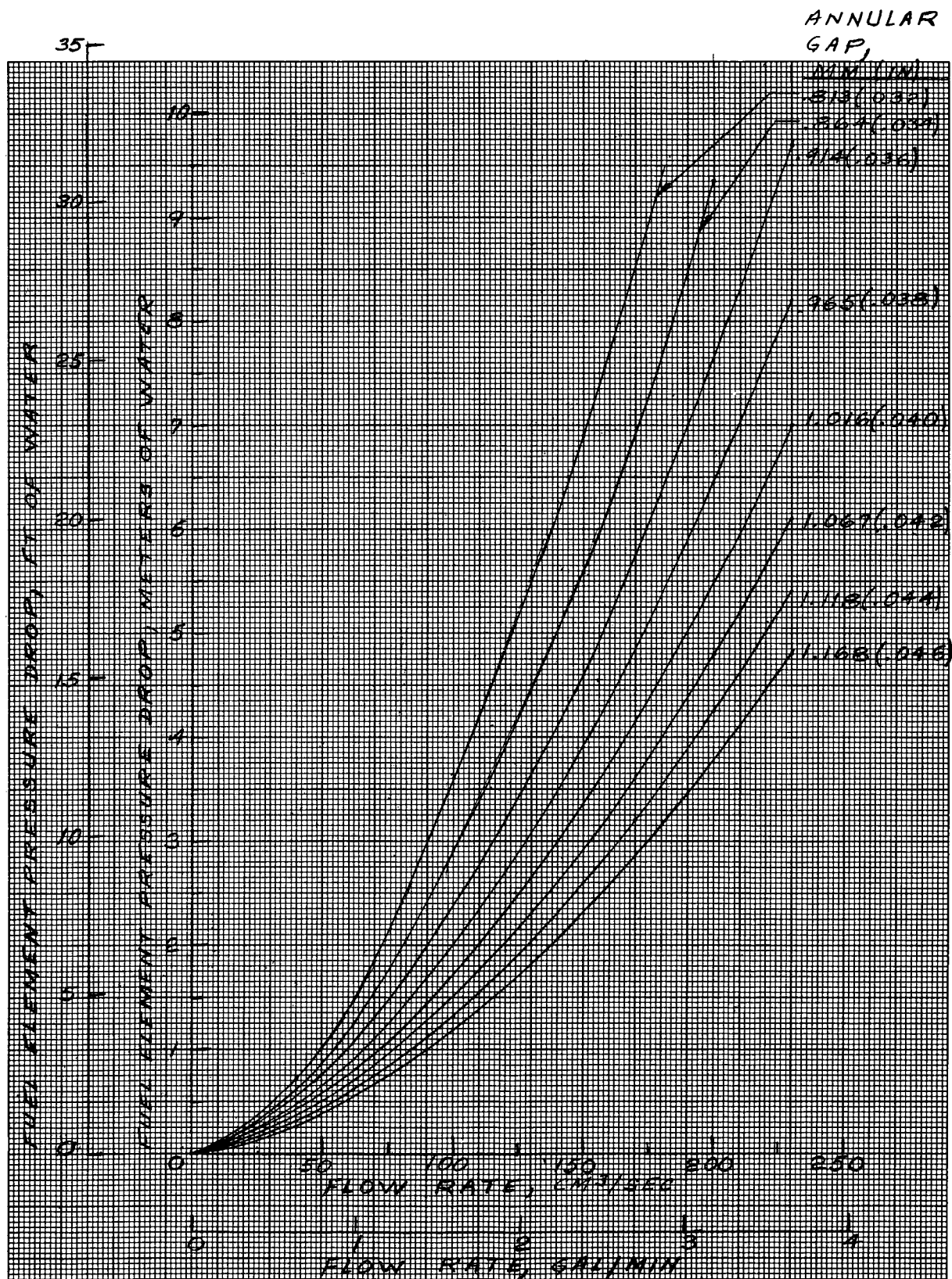
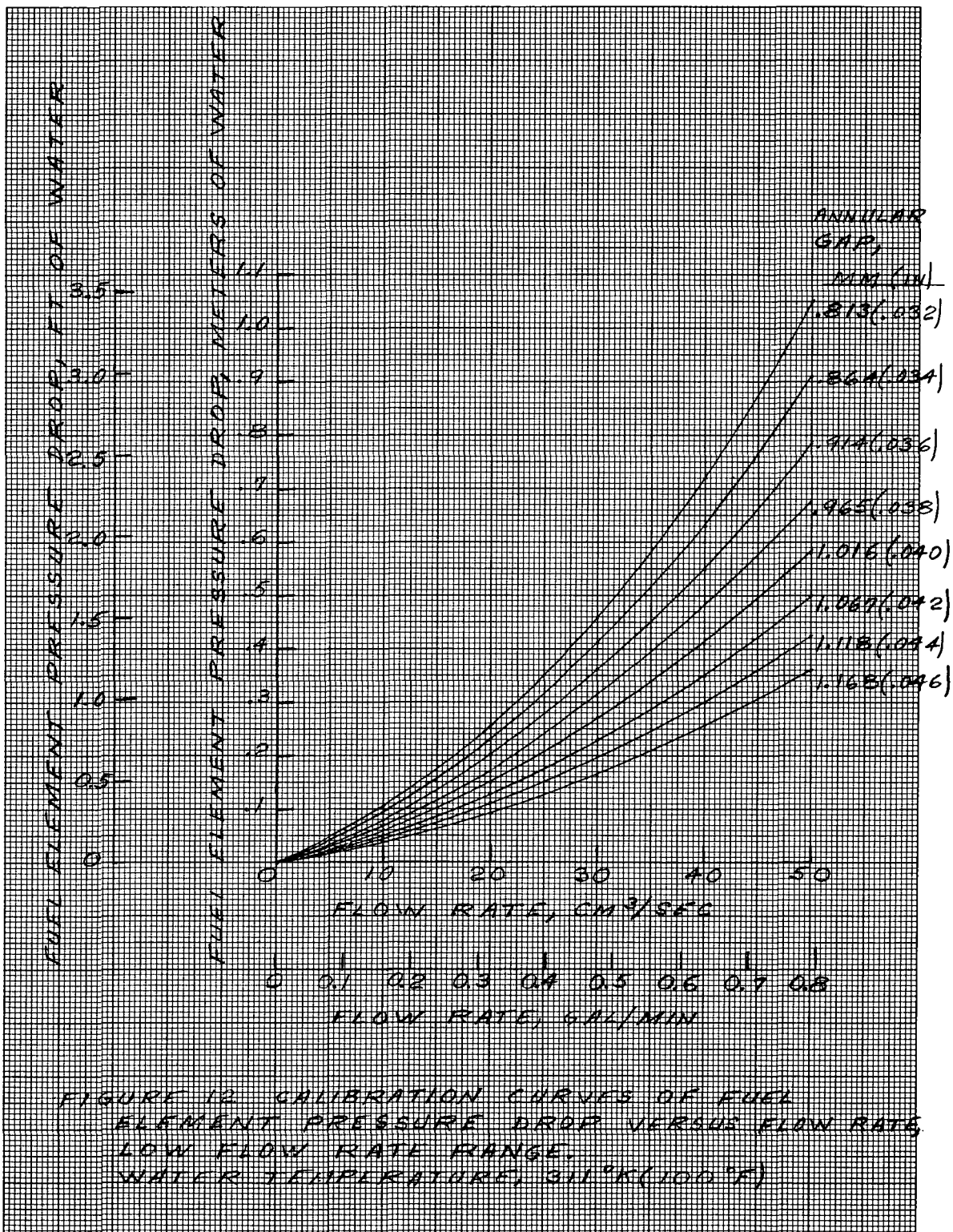
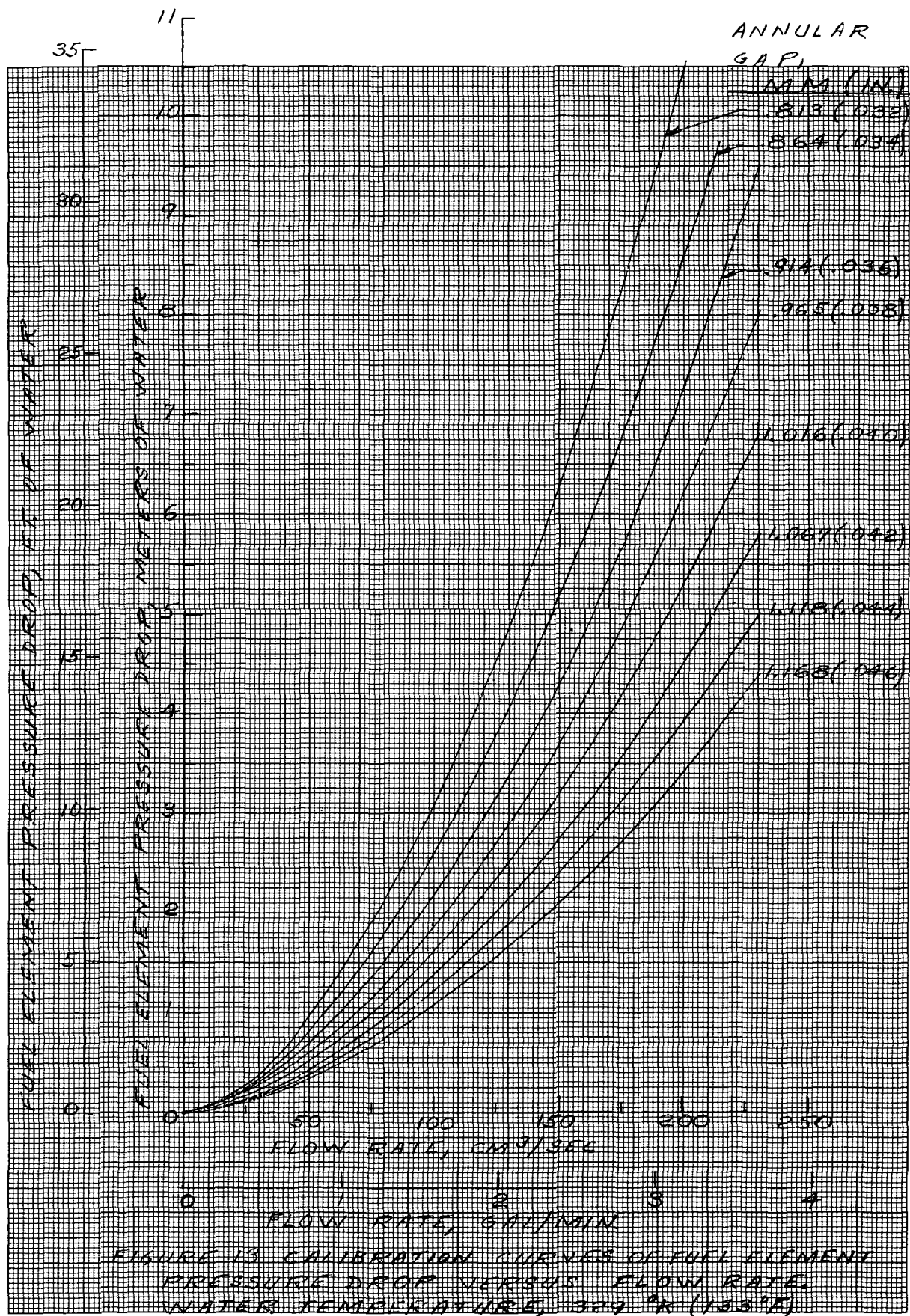


FIGURE 11. CALIBRATION CURVES OF FUEL ELEMENT PRESSURE DROP VERSUS FLOW RATE. WATER TEMPERATURE, 311°K (100°F)





FUEL ELEMENT PRESSURE DROP, IT OF WATER

3.0
2.0
1.0
0

FUEL ELEMENT PRESSURE DROP, MM H₂O

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

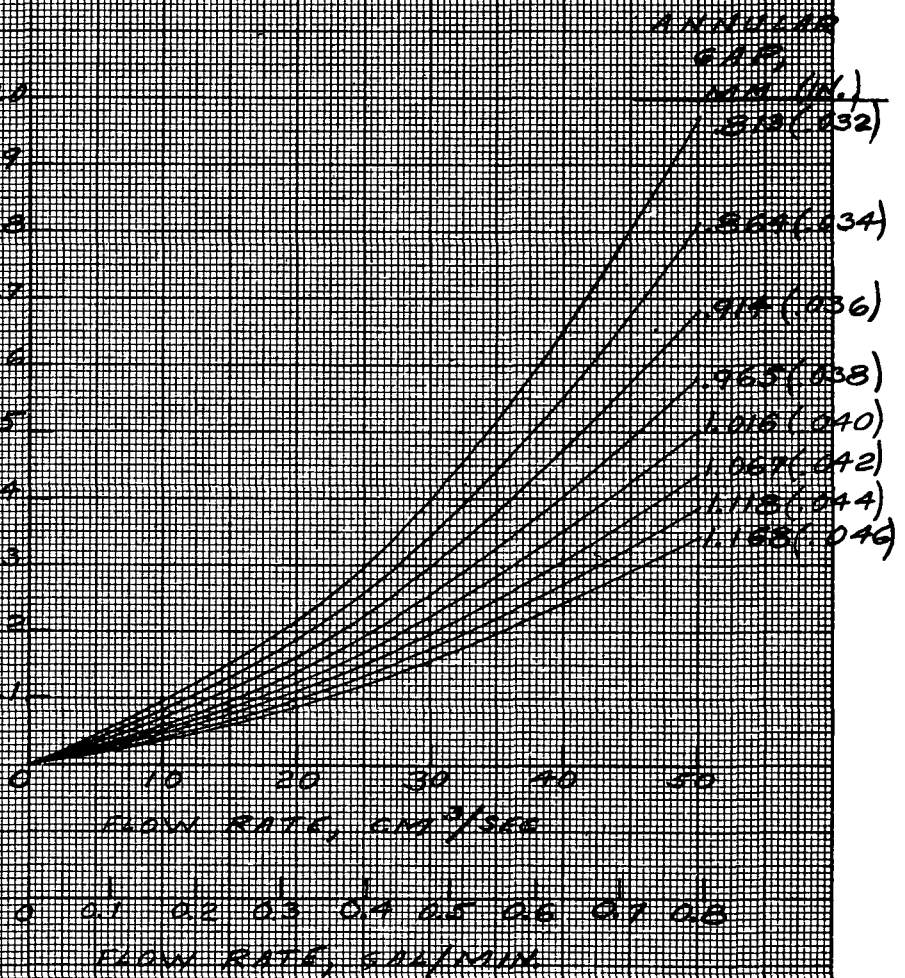


FIGURE 14. CALIBRATION CURVES OF FUEL ELEMENT PRESSURE DROP VERSUS FLOW RATE, LOW FLOW RATE RANGE, WATER TEMPERATURE, 329 °K (133 °F)

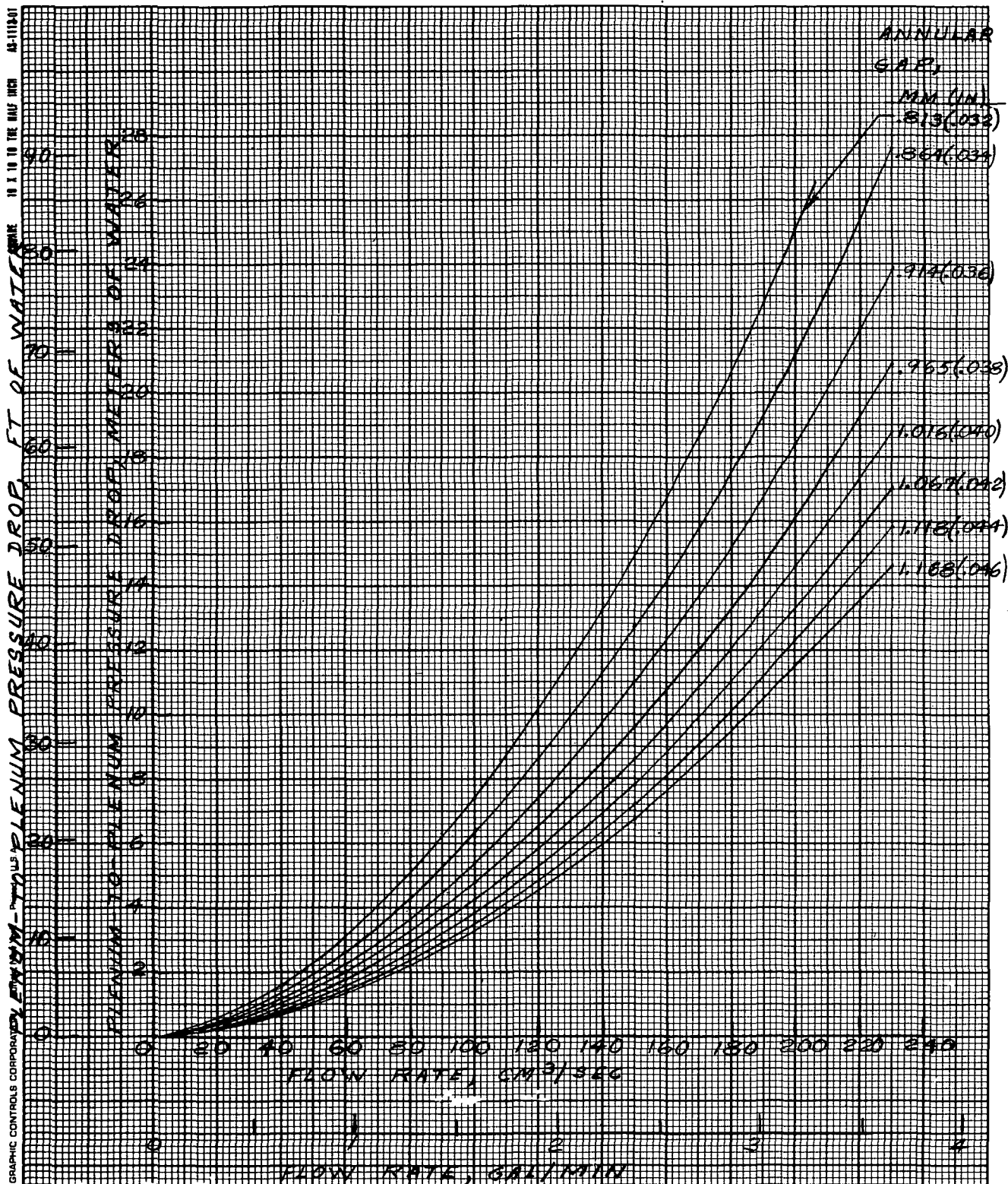
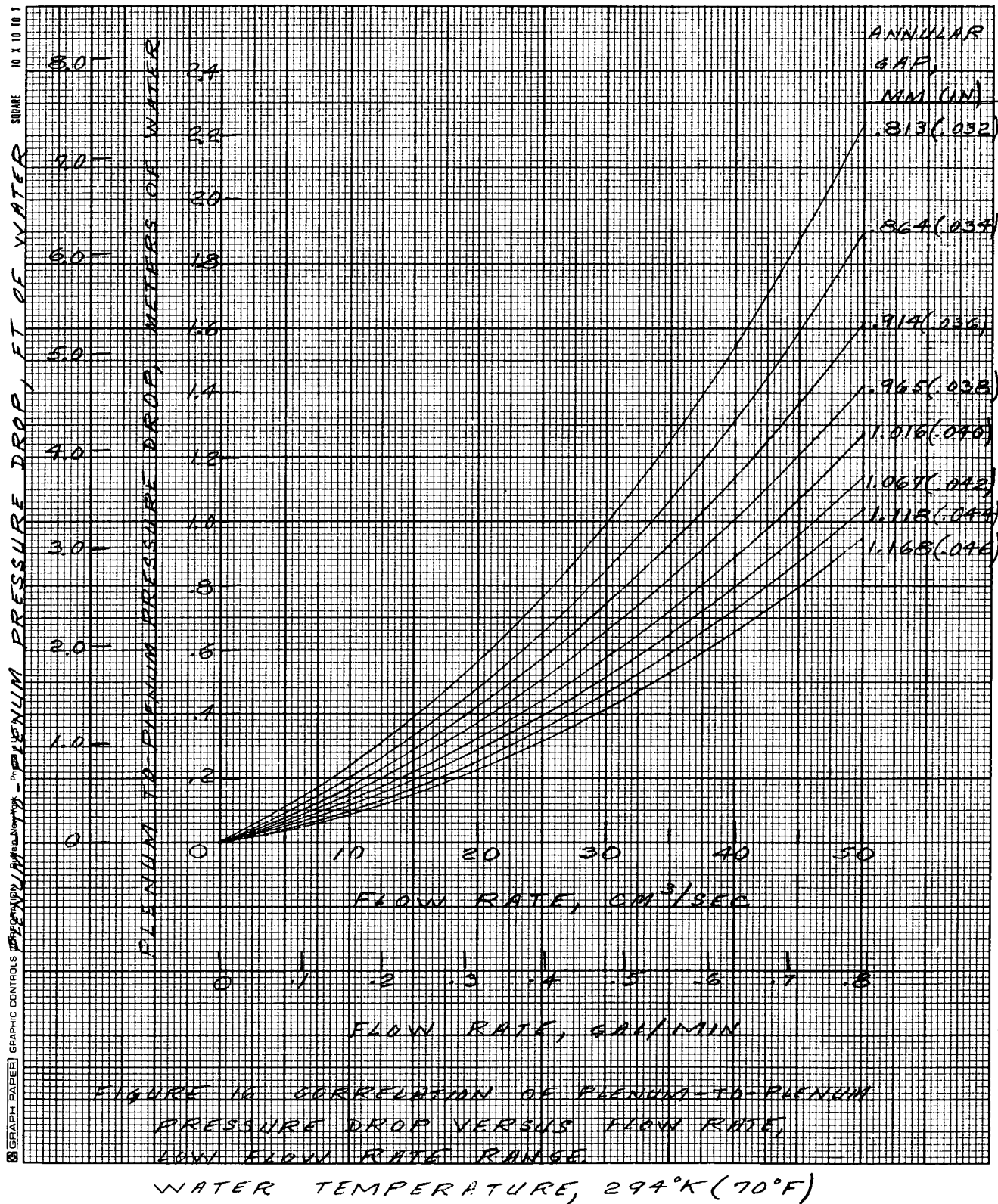
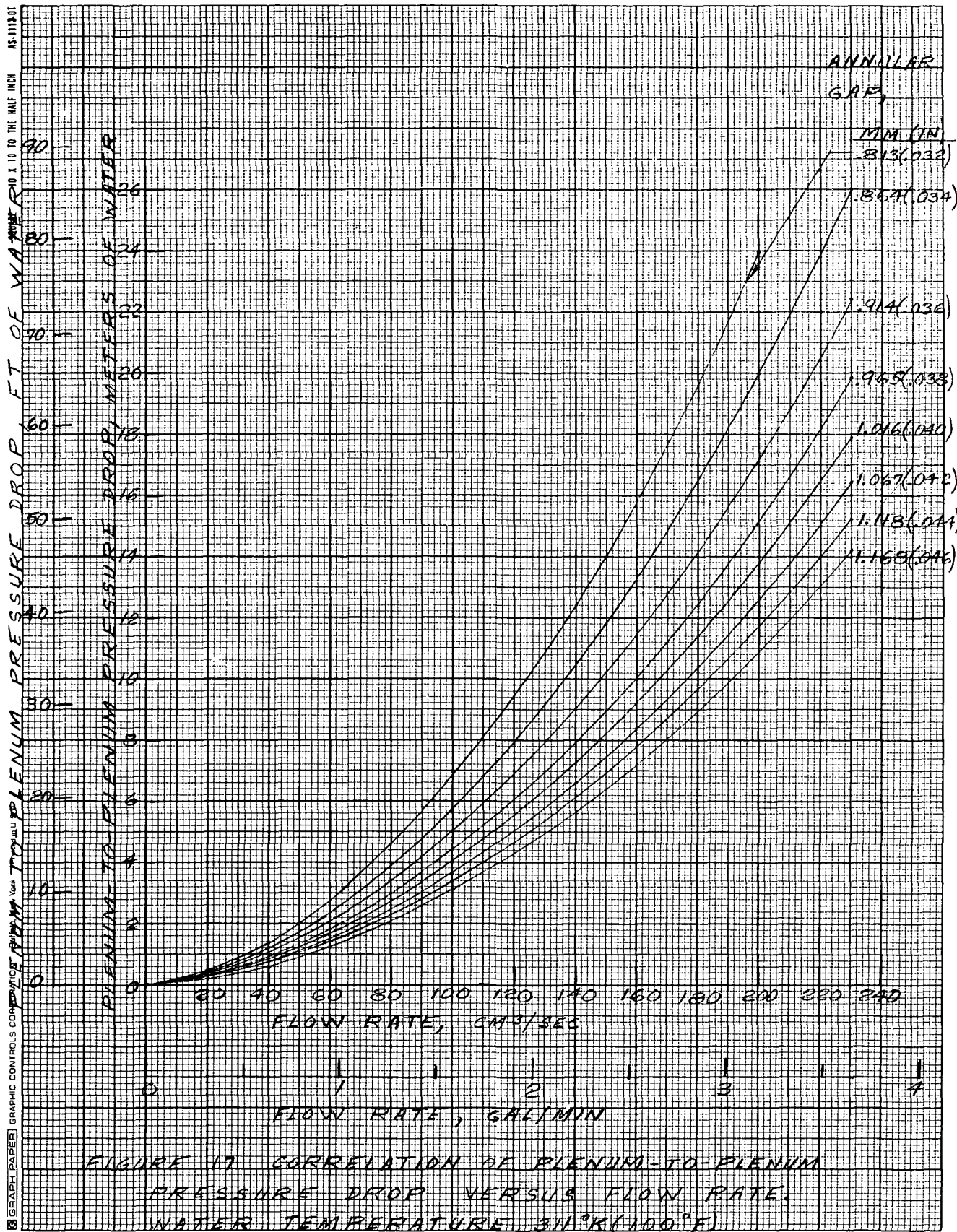


FIGURE 15 CORRELATION OF PLENUM-TO-PLENUM PRESSURE DROP VERSUS FLOW RATE. WATER TEMPERATURE, 299.4°K (70°F).





ANNULAR
GAP,

MM (IN)

.813 (.032)

.864 (.034)

.914 (.036)

.965 (.038)

1.016 (.040)

1.067 (.042)

1.118 (.044)

1.168 (.046)

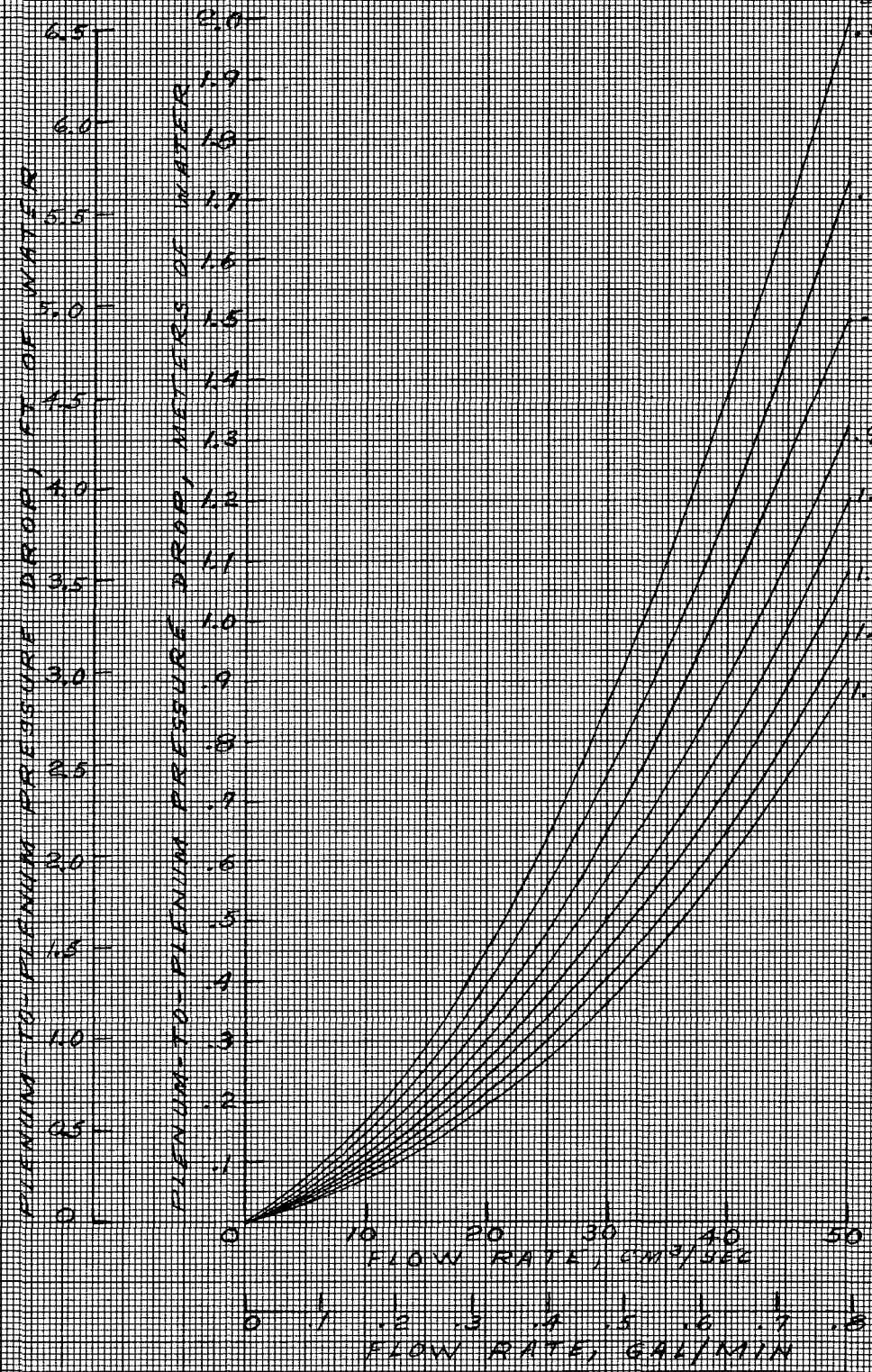
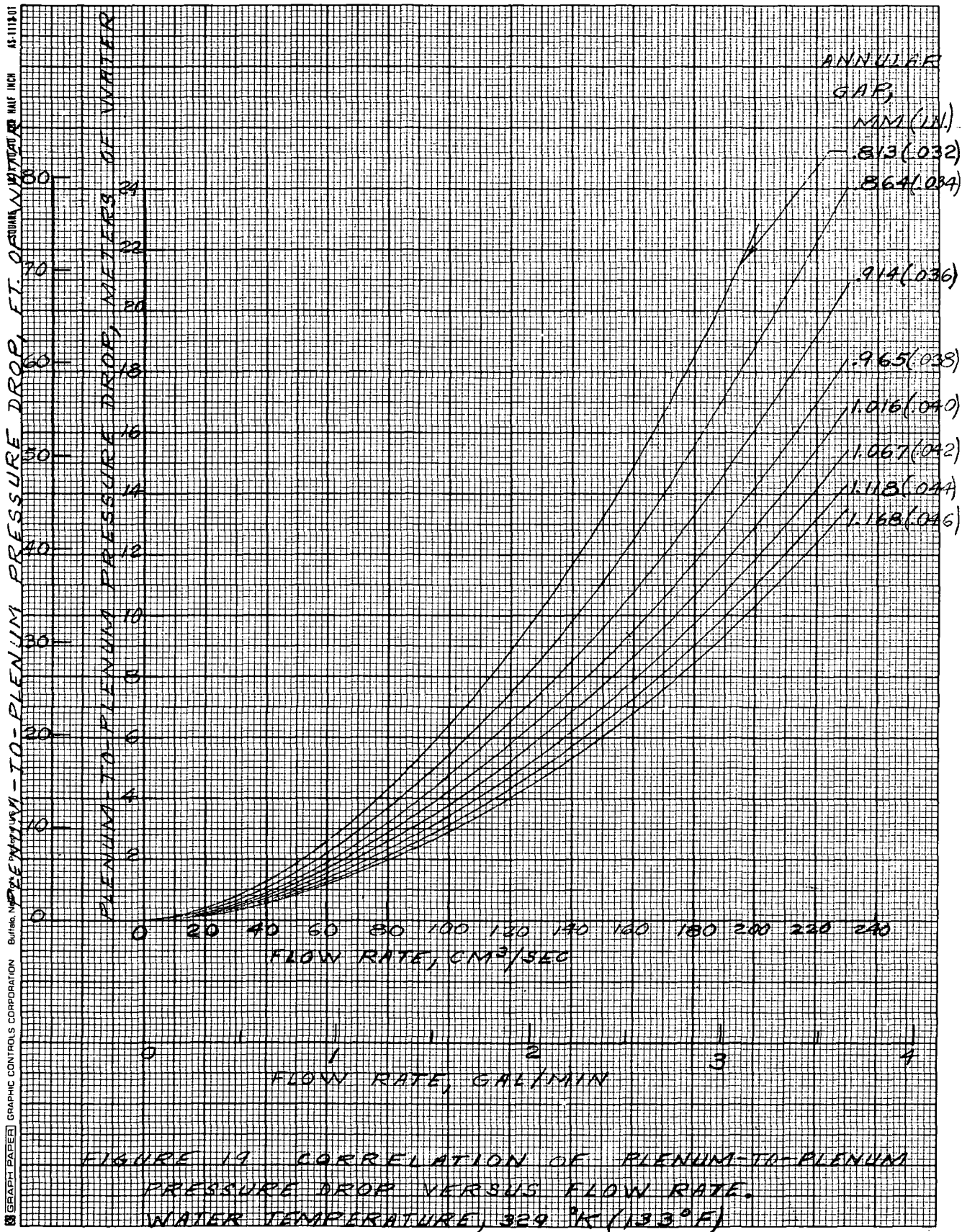


FIGURE IS CORRELATION OF PLENUM TO PLENUM
PRESSURE DROP VERSUS FLOW RATE,
LOW FLOW RATE RANGE.

WATER TEMPERATURE, 311°K (100°F)



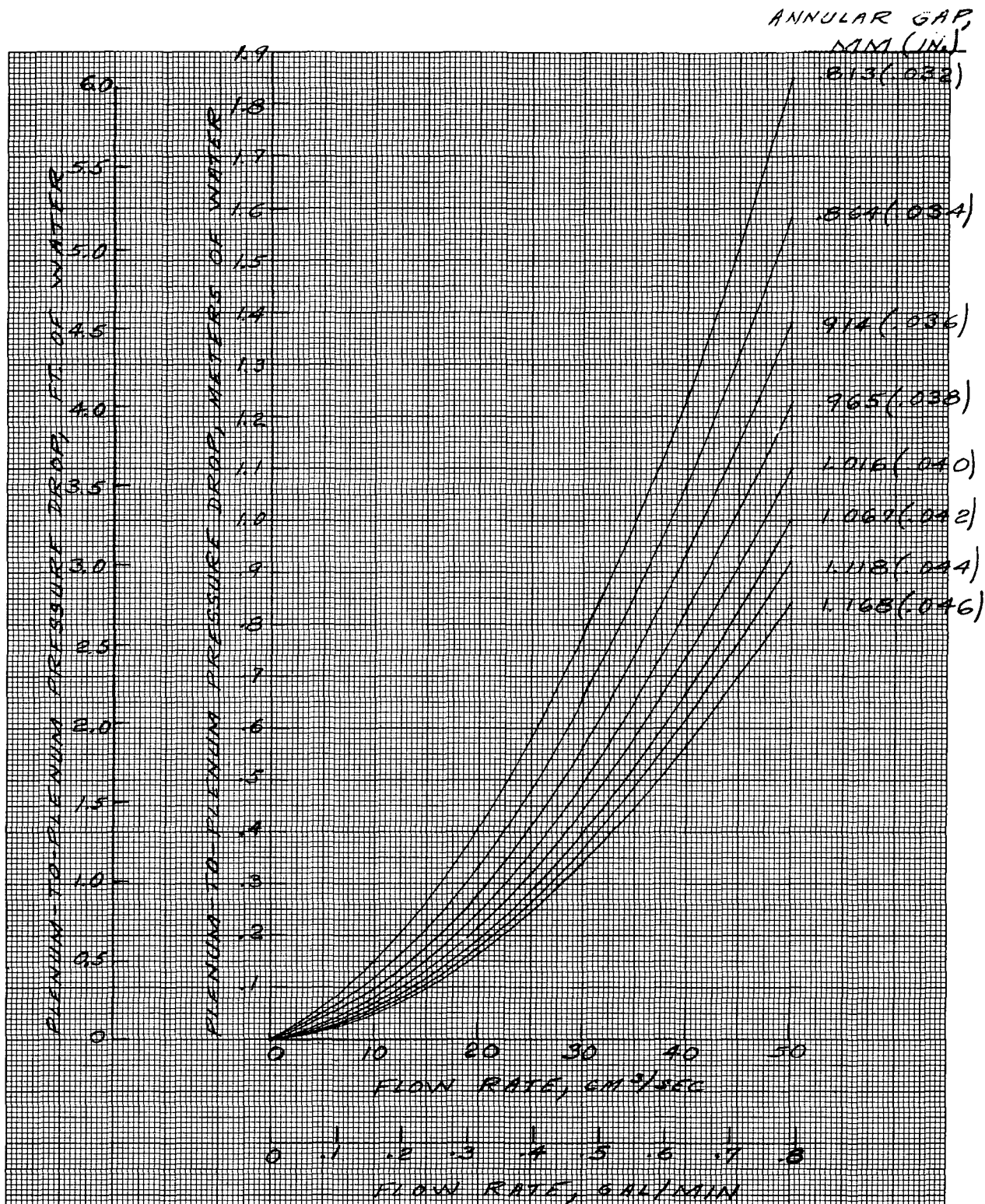
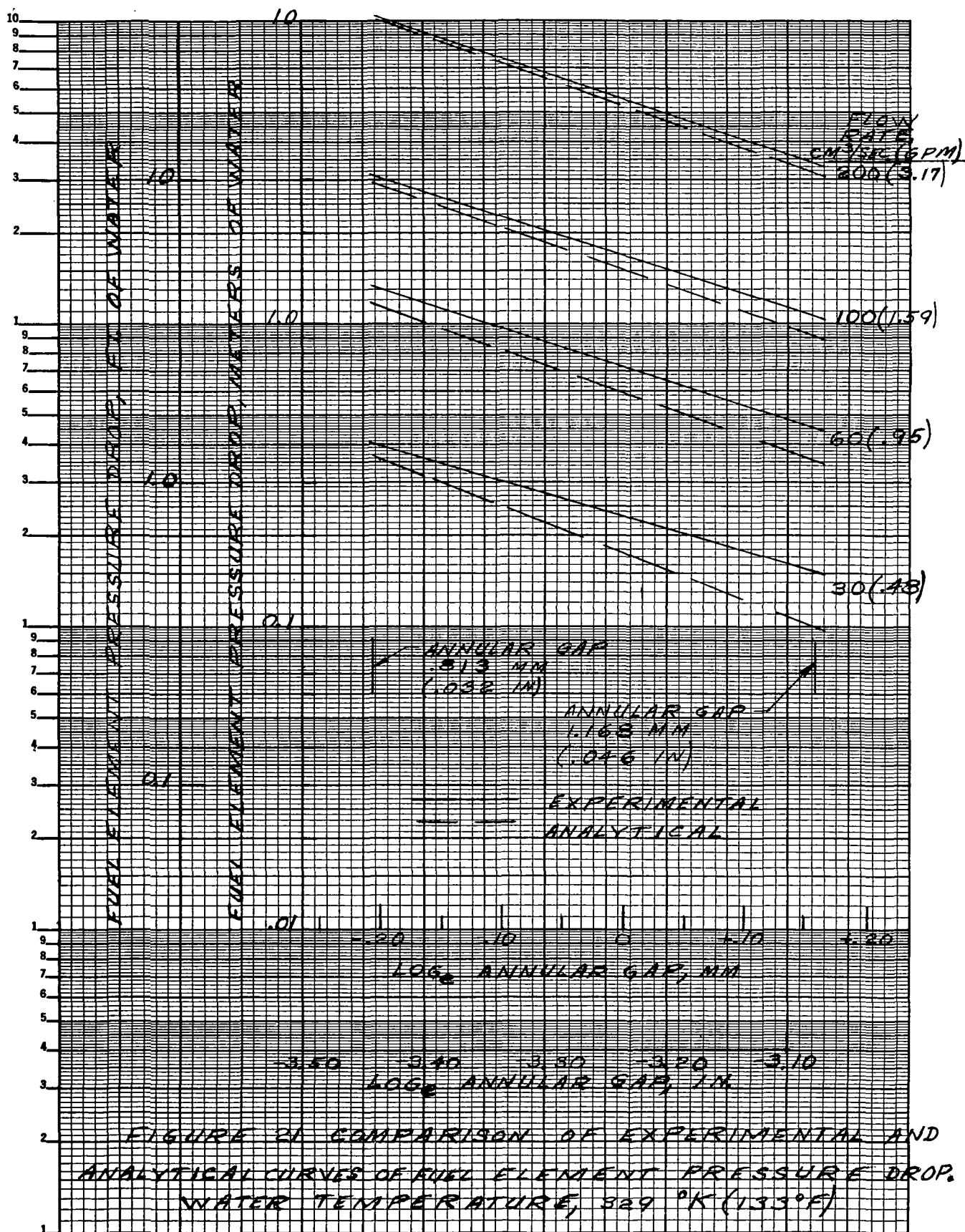


FIGURE 20 CORRELATION OF PLENUM-TO-PLENUM PRESSURE DROP VERSUS FLOW RATE, LOW FLOW RATE RANGE, WATER TEMPERATURE, 329 °K (133 °F)



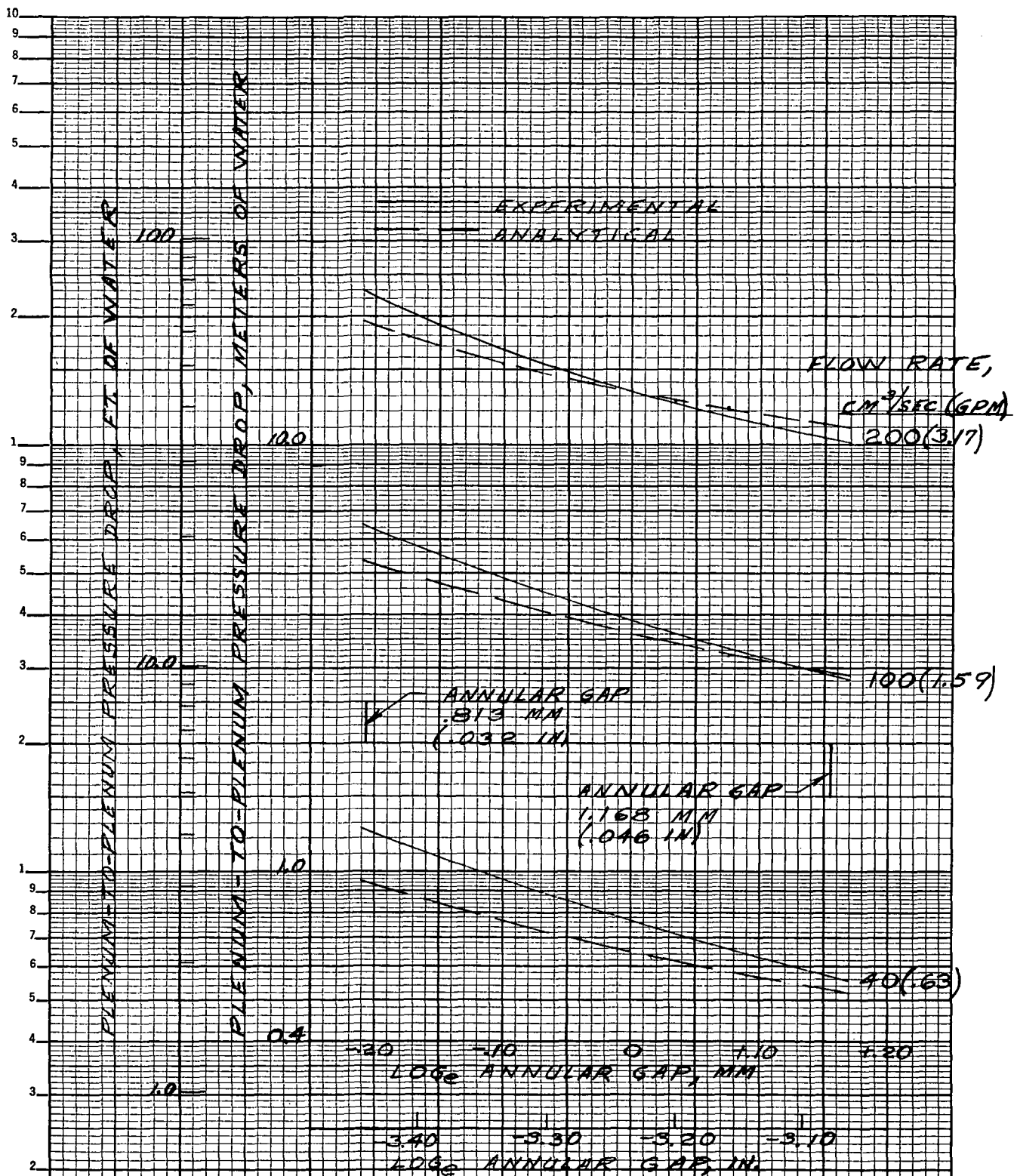
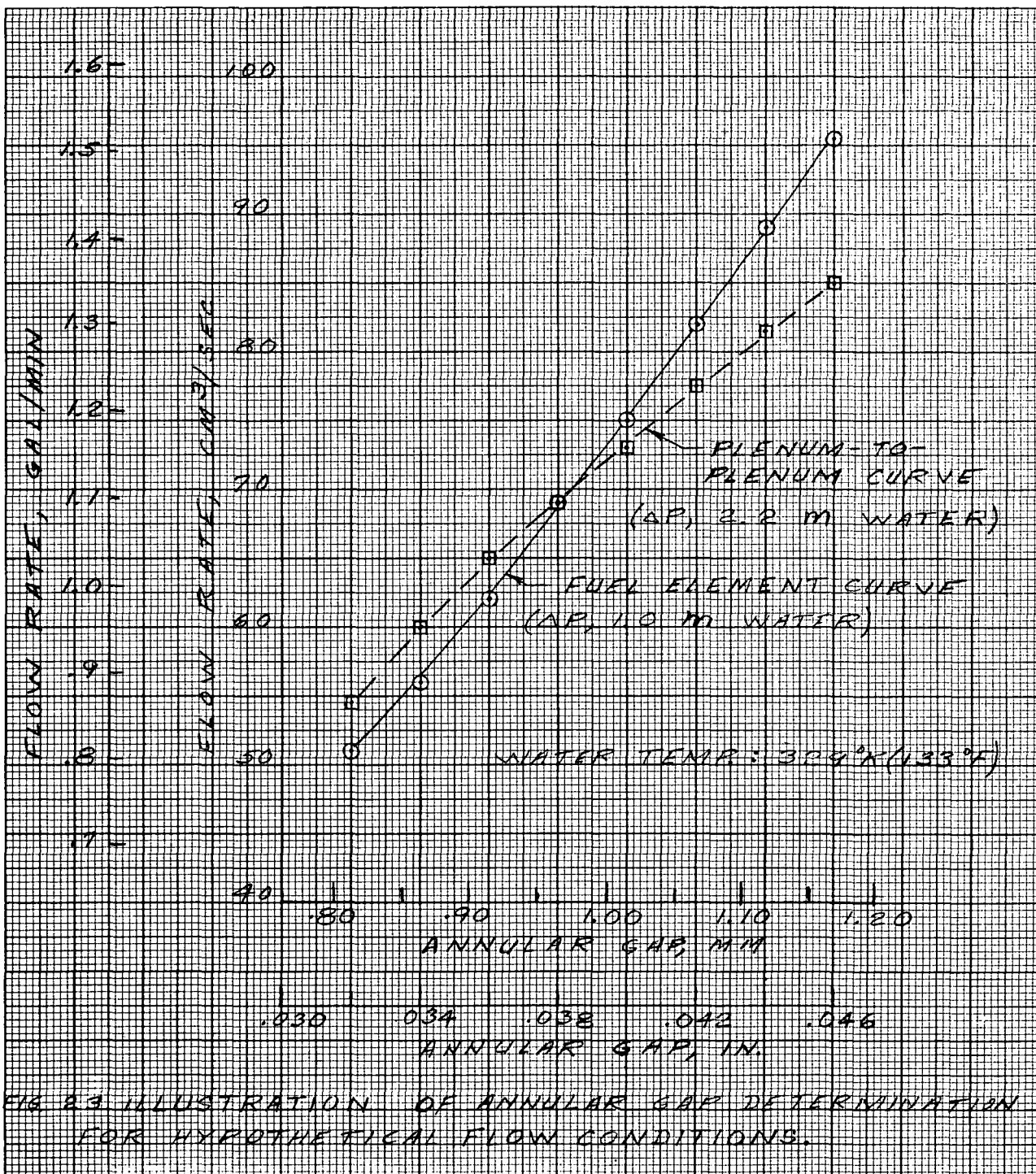


FIGURE 22 COMPARISON OF EXPERIMENTAL AND ANALYTICAL CURVES OF PLENUM-TO-PLENUM PRESSURE DROP. WATER TEMP, 329 °K (133 °F)



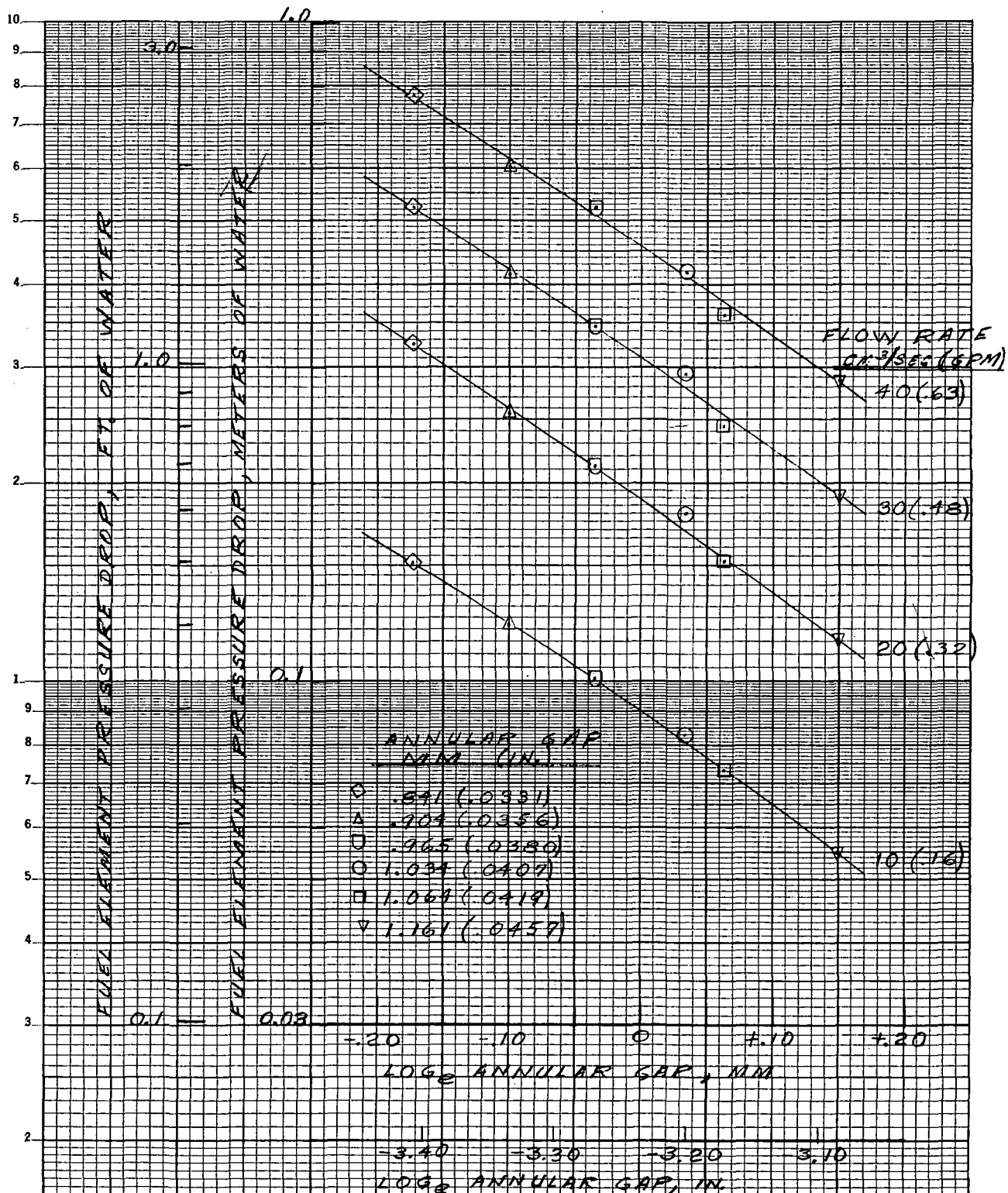


FIGURE 24 EFFECT OF ANNULUS WIDTH ON FUEL ELEMENT PRESSURE DROP - LOW FLOW RATE RANGE.

WATER TEMP, 294°K (70°F)

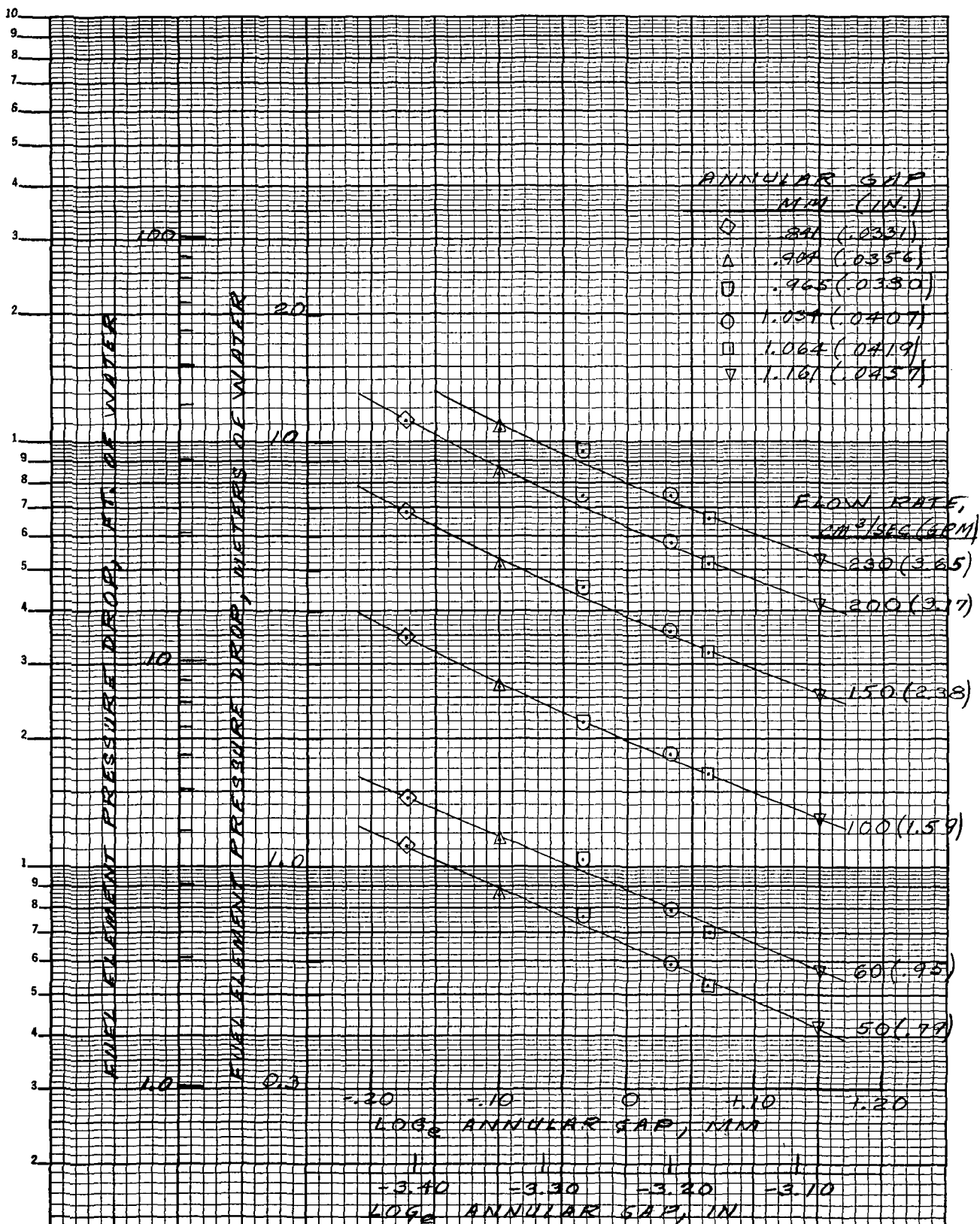


FIGURE 25 EFFECT OF ANNULAR WIDTH ON FUEL ELEMENT PRESSURE DROP - HIGH FLOW RATE RANGE
WATER TEMP, 294°K (70°F)

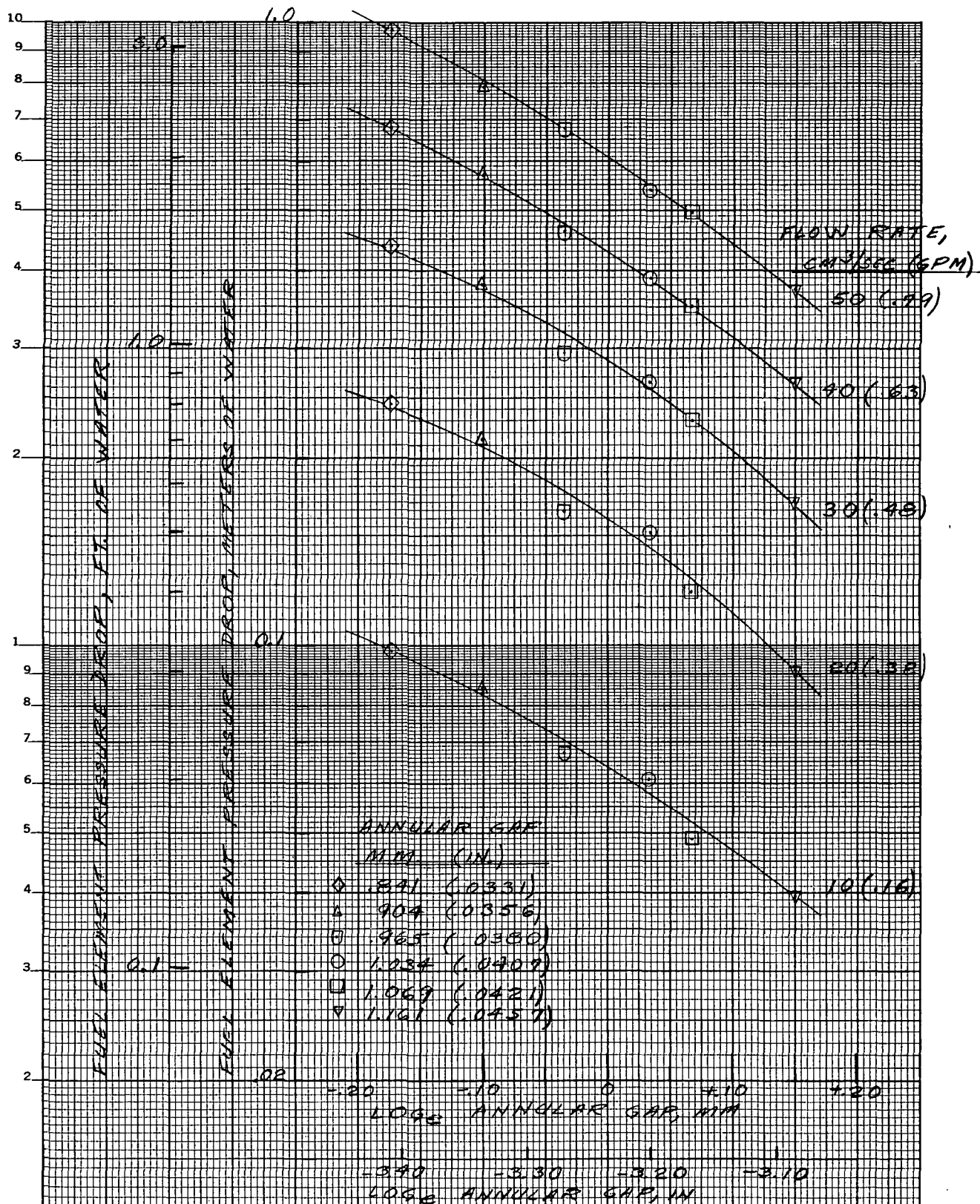
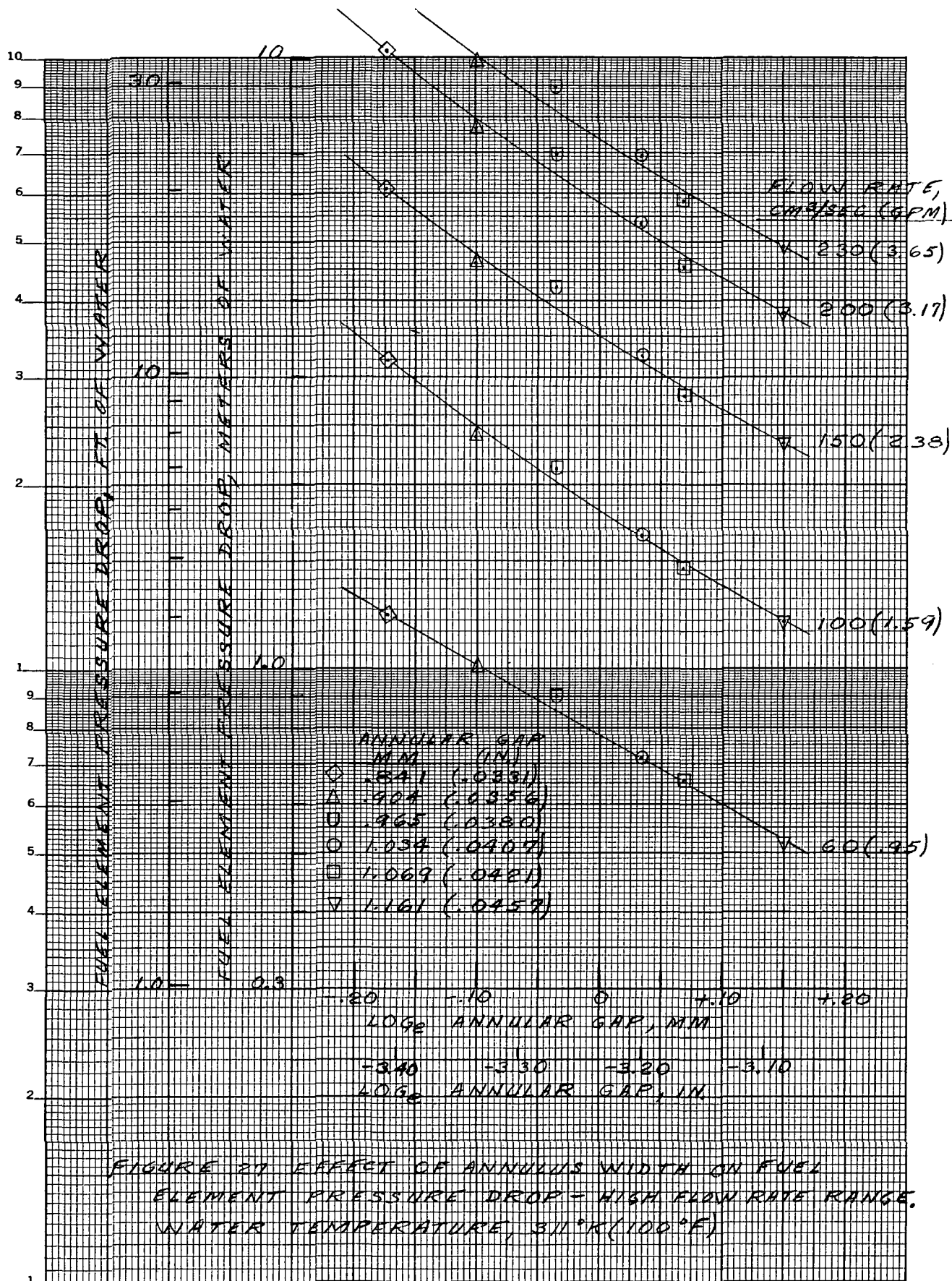


FIGURE 26 EFFECT OF ANNULUS WIDTH ON FUEL
ELEMENT PRESSURE DROP—LOW FLOW RATE RANGE.
WATER TEMPERATURE, 311°K (100°F)



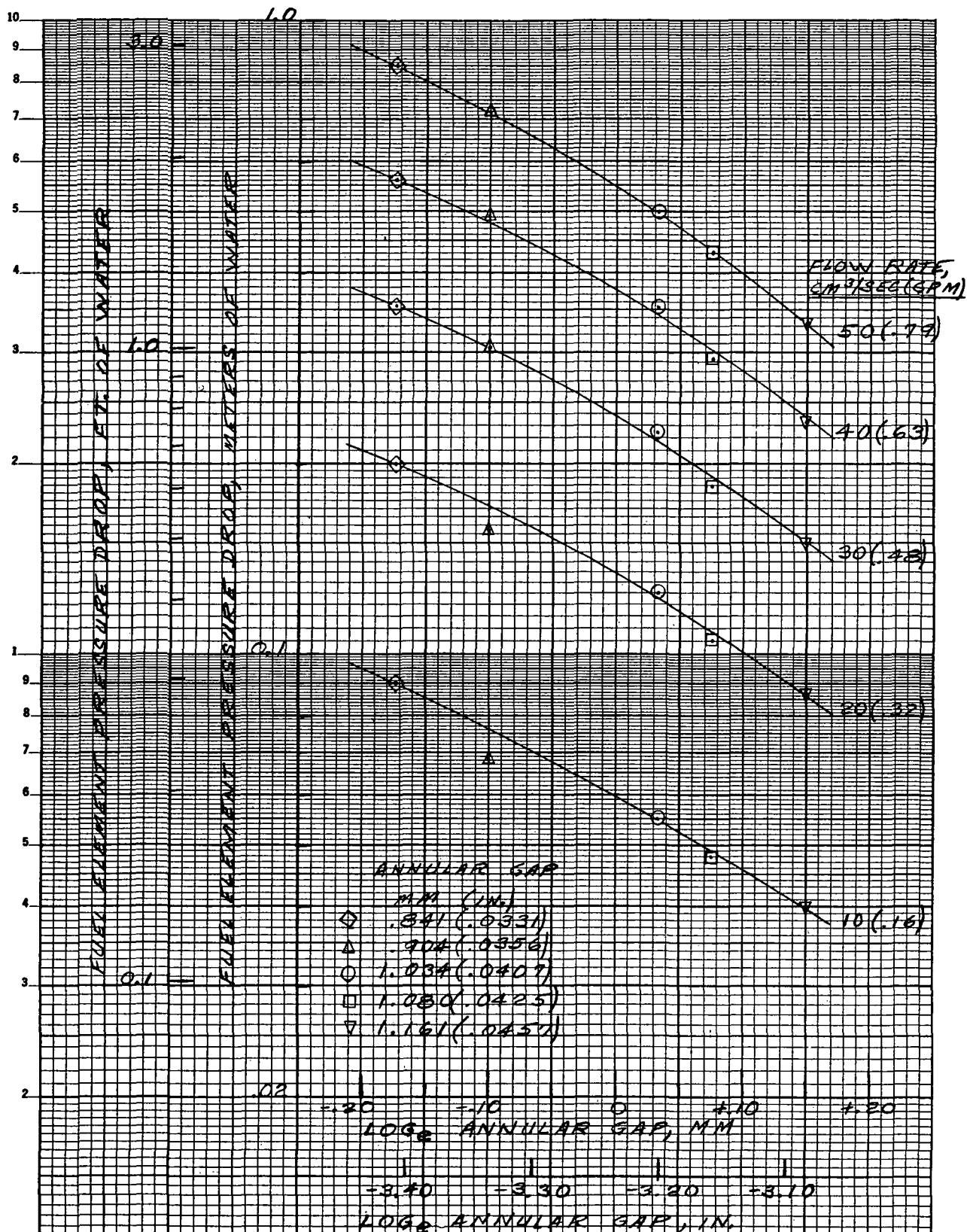


FIGURE 28 EFFECT OF ANNULUS WIDTH ON FUEL ELEMENT PRESSURE DROP - LOW FLOW RATE RANGE,

WATER TEMP, 329°K (133°F)

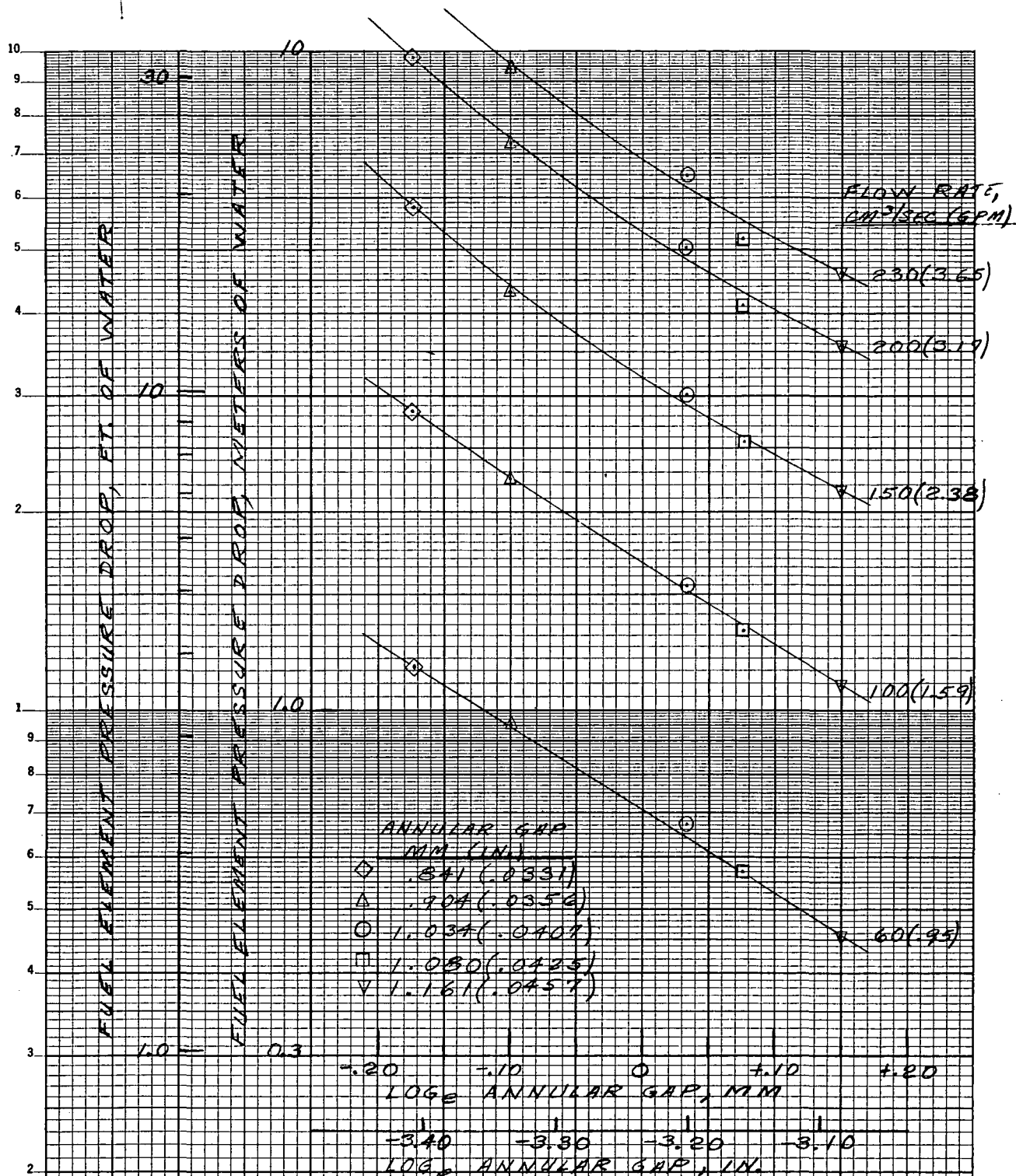
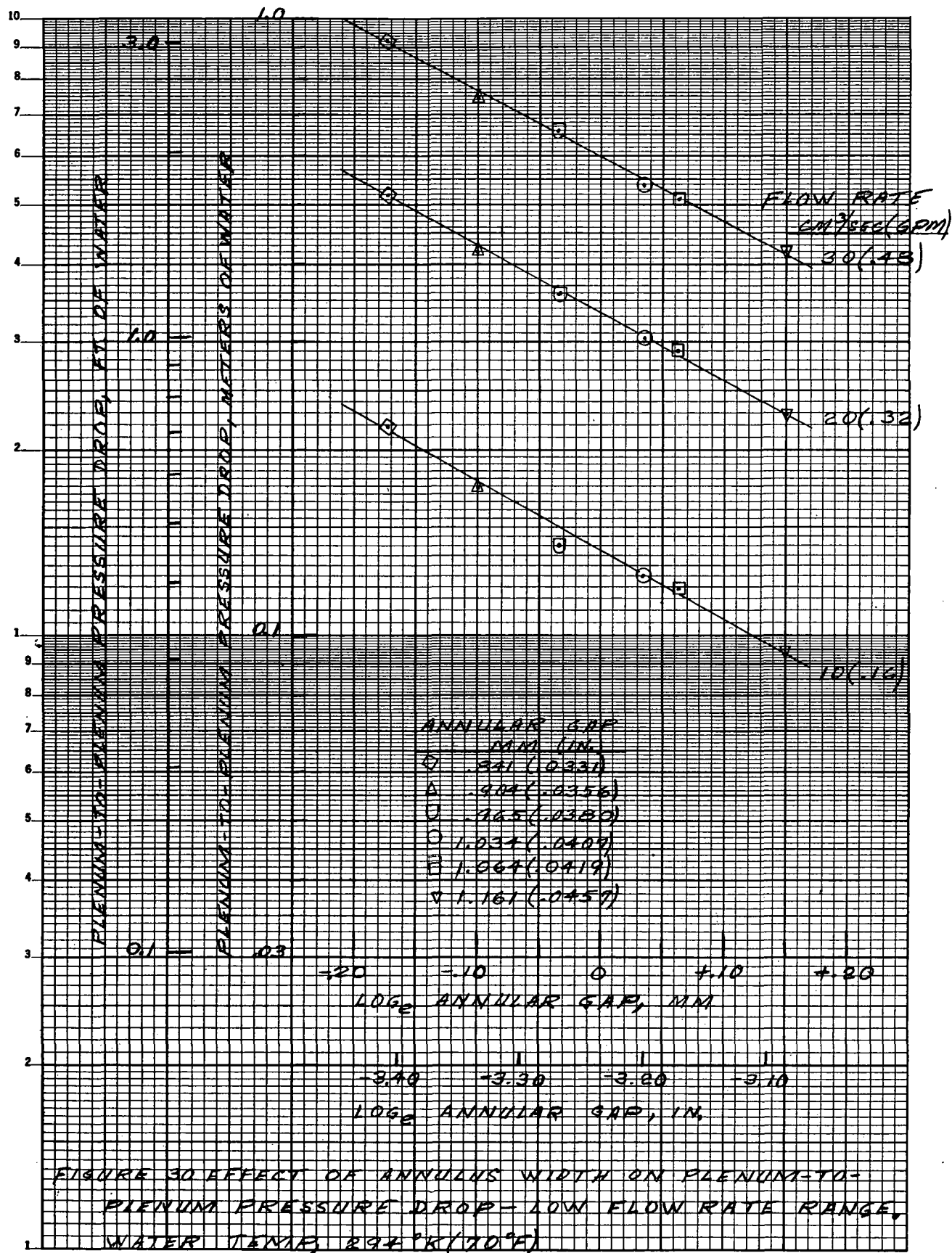


FIGURE 29 EFFECT OF ANNULUS WIDTH ON FUEL ELEMENT PRESSURE DROP - HIGH FLOW RATE RANGE. WATER TEMP, 329°K (133°F)



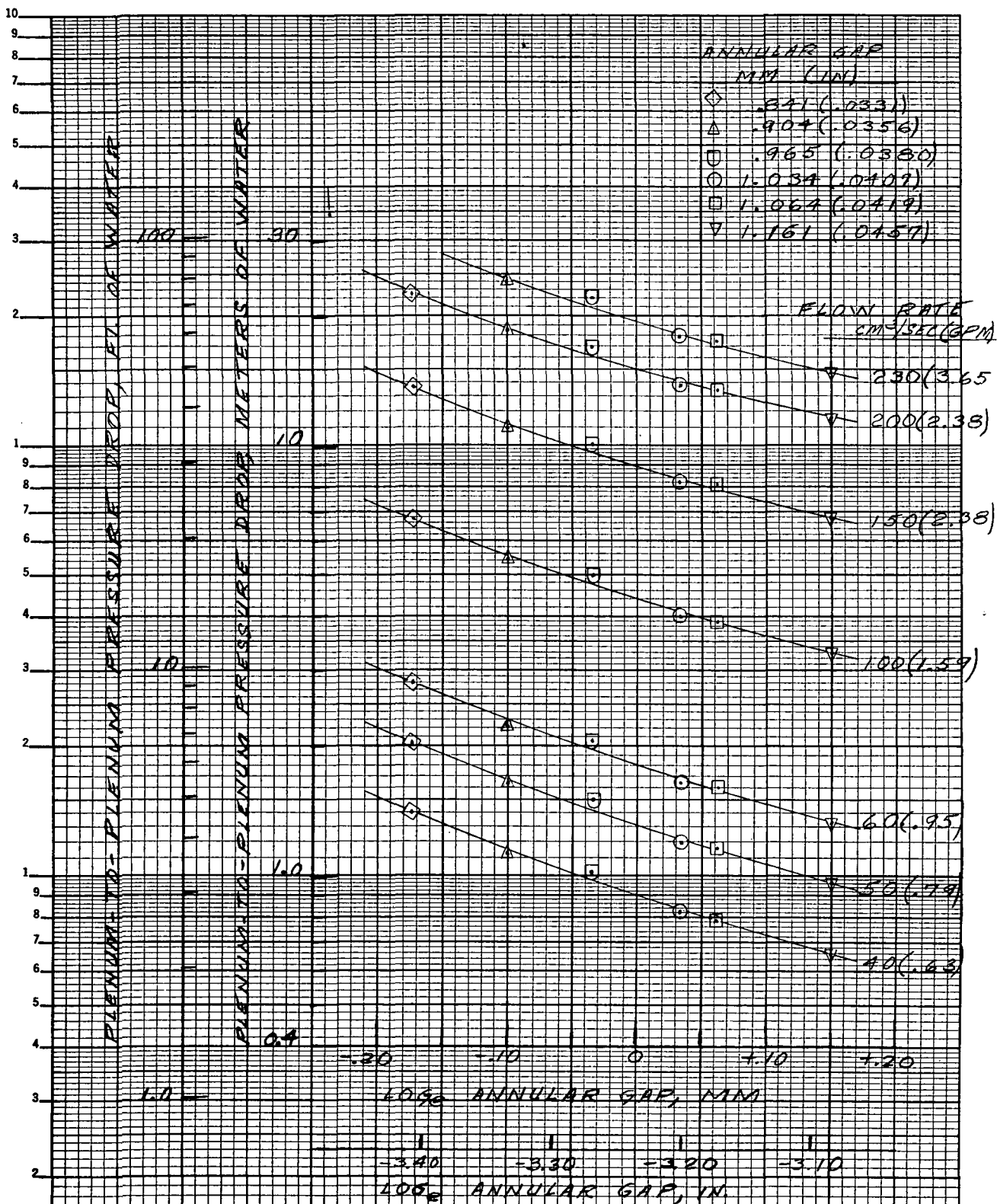
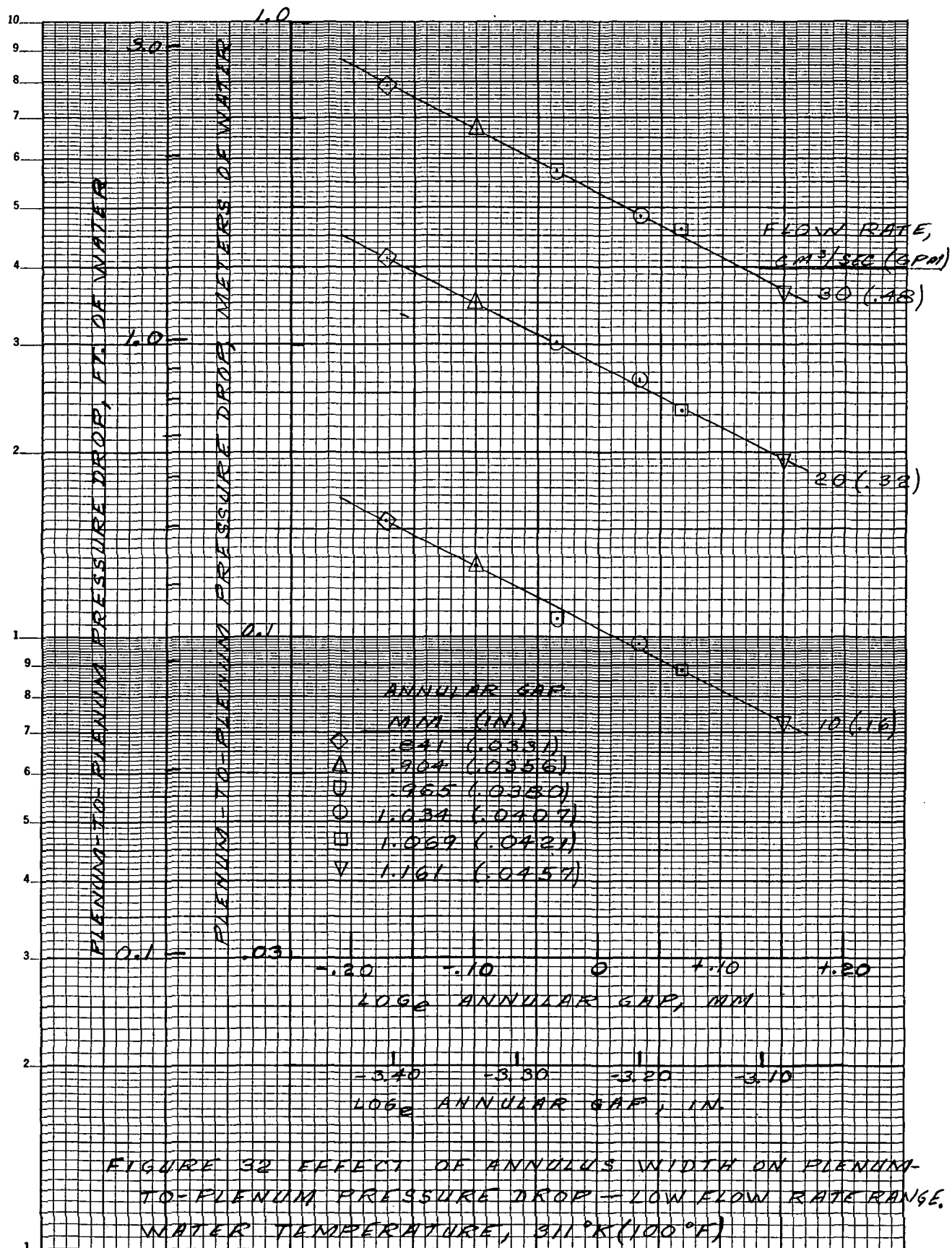


FIGURE 31 EFFECT OF ANNULUS WIDTH ON PLENUM-TO-
PLENUM PRESSURE DROP - HIGH FLOW RATE RANGE.
WATER TEMP, 294°K (70°F)



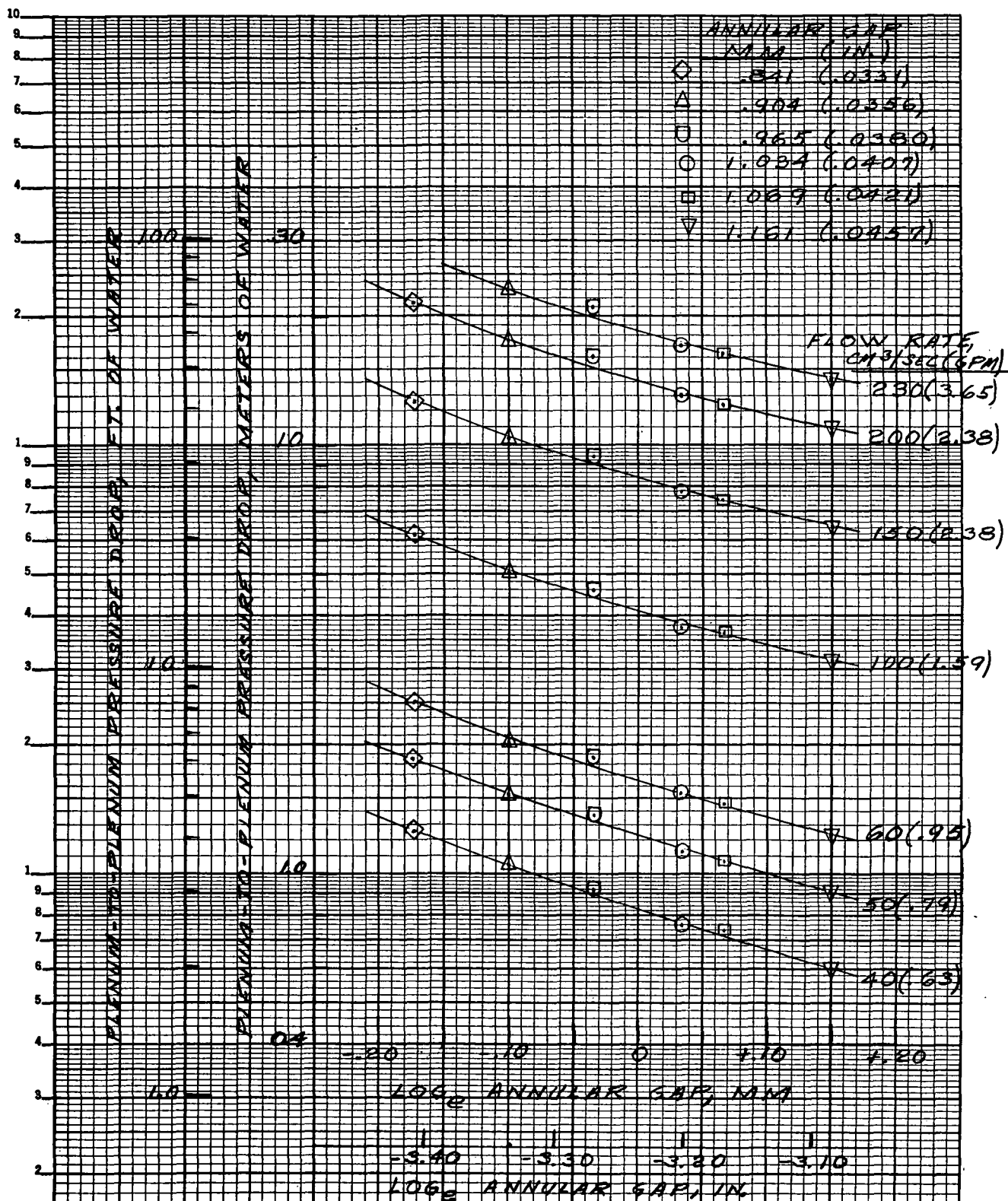
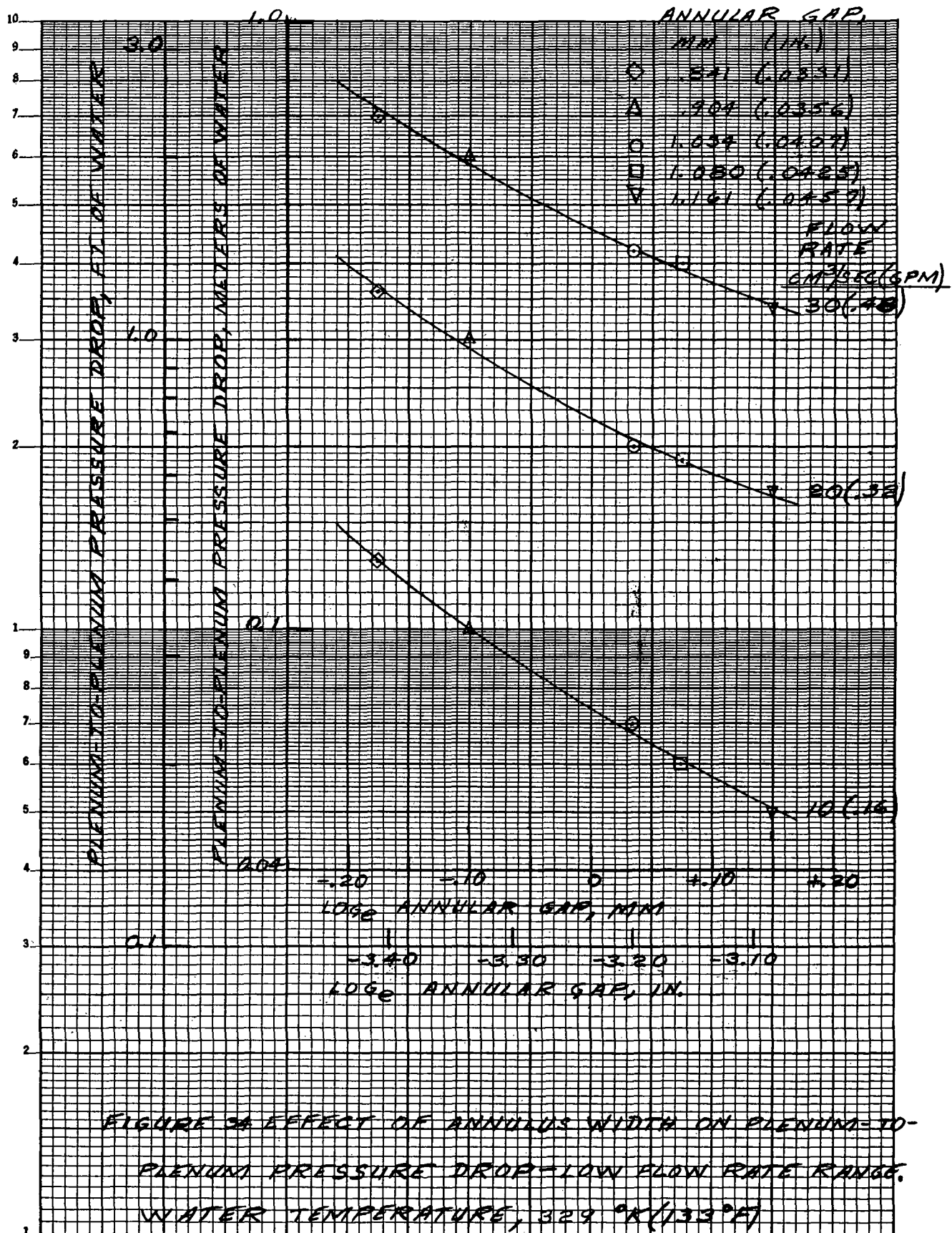


FIGURE 33 EFFECT OF ANNULUS WIDTH ON PLENUM-TO-
 PLENUM PRESSURE DROP-HIGH FLOW RATE RANGE.
 WATER TEMPERATURE, 311°K (100°F)



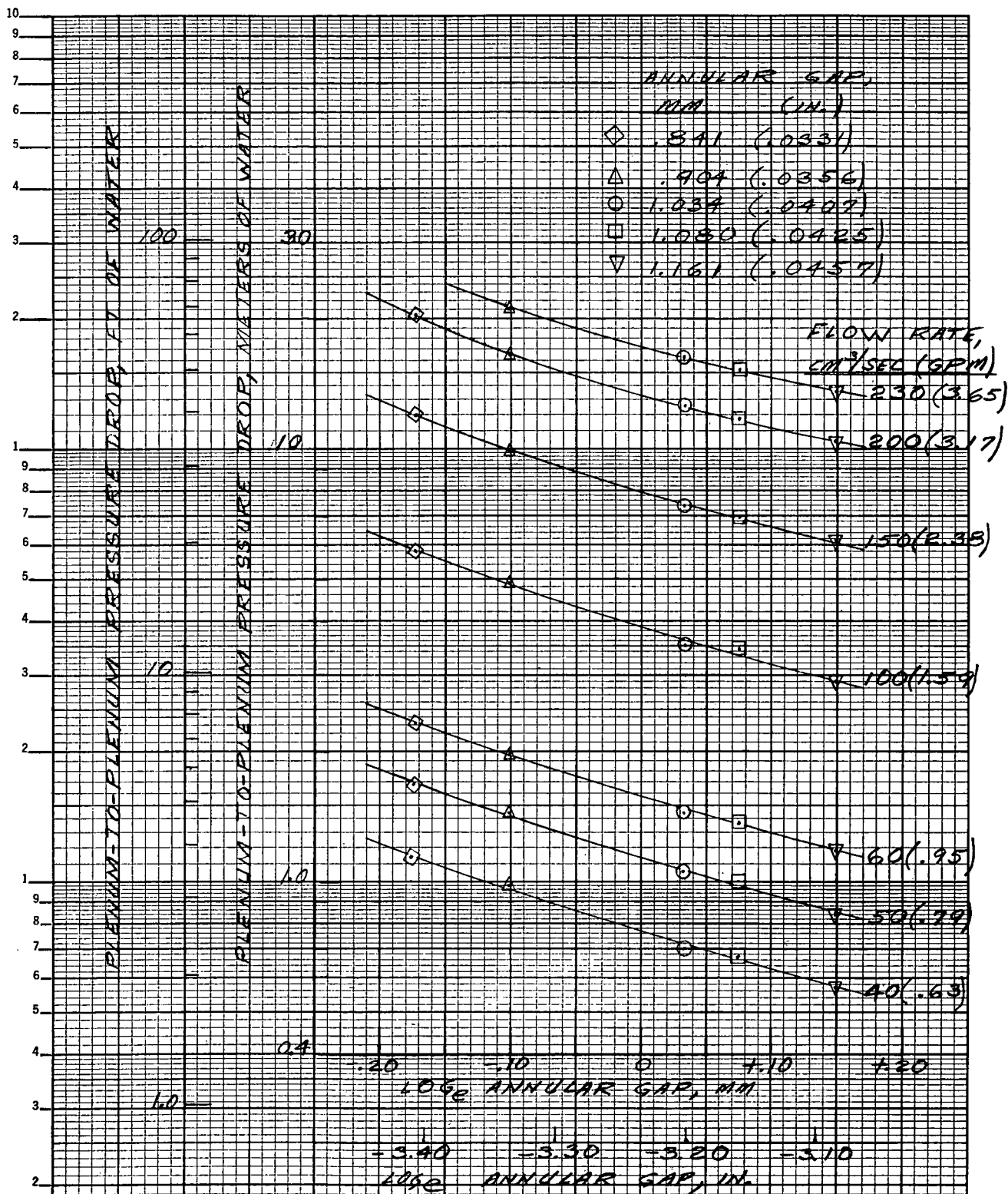


FIGURE 35 EFFECT OF ANNULUS WIDTH ON PLENUM-TO-
PLENUM PRESSURE DROP - HIGH FLOW RATE RANGE.
WATER TEMPERATURE, 329 °K (133 °F)

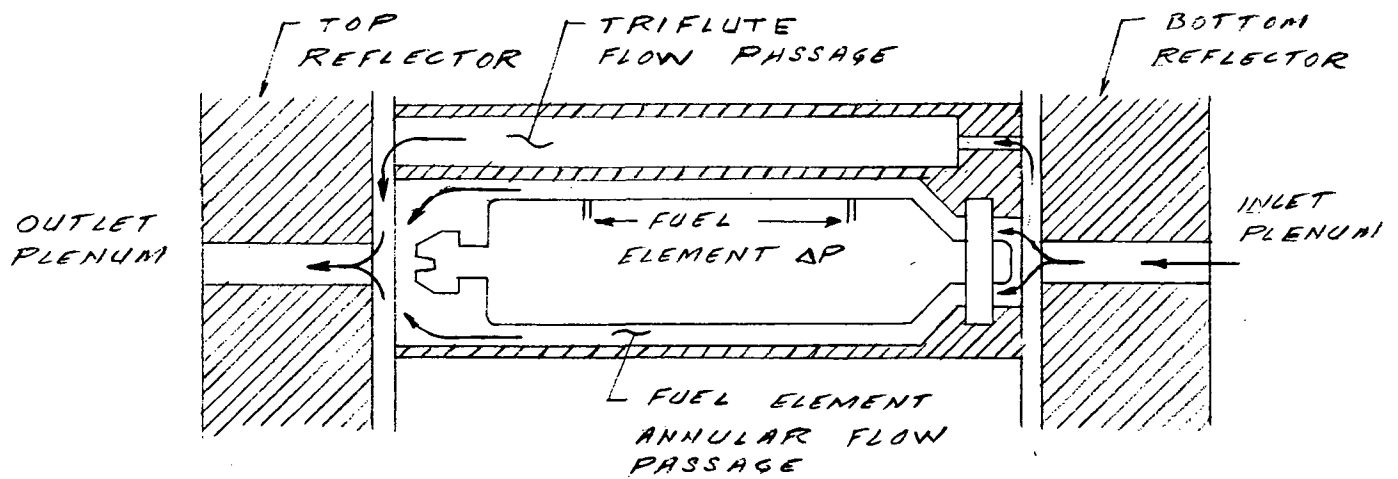


FIGURE 36 - SCHEMATIC OF TYPICAL FUEL ELEMENT AND TRIFLUTE FLOW PASSAGE IN REACTOR.